Exploring the Role of Surface Waves, Wave-Current Interaction, and Wave Breaking in Modulating the Coupling between the Ocean and the Atmosphere

Luc Lenain, Kayli Matsuyoshi, Laurent Grare, Nick Statom

Scripps Institution of Oceanography
& many more collaborators

A multiscale observational approach to Air-Sea Interaction research

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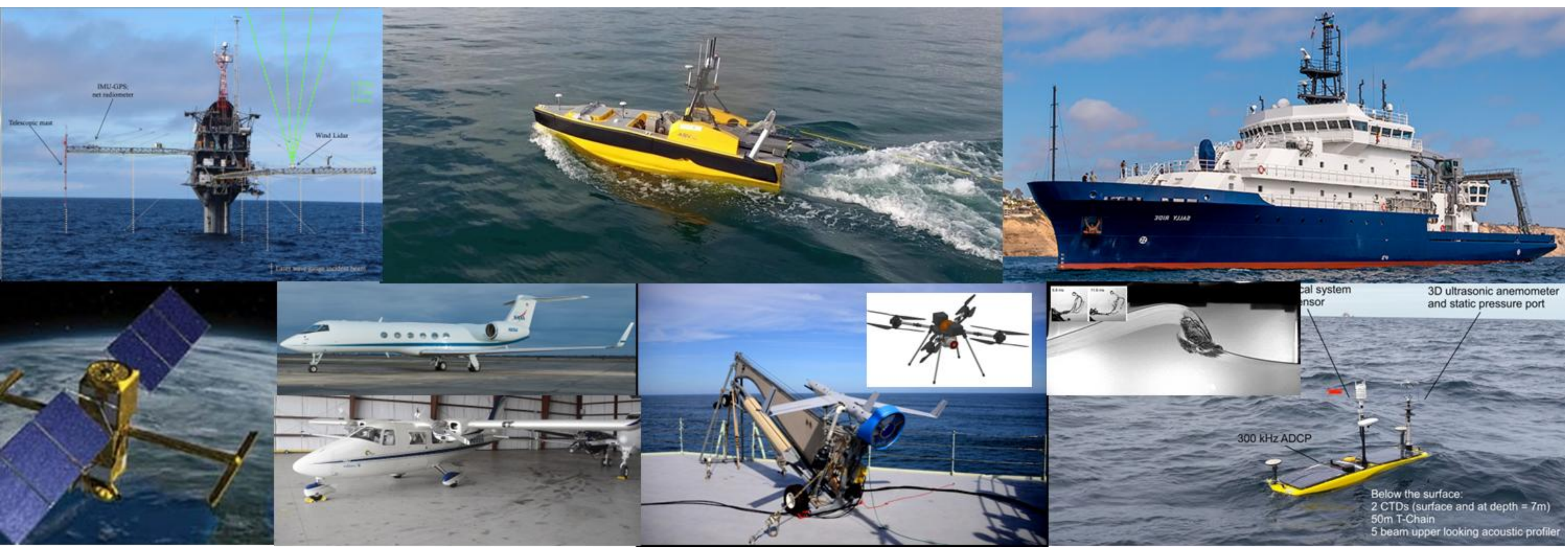
Recent progress on better understanding the **role of surface gravity waves and wave breaking in air-sea interaction and submesoscale dynamics**

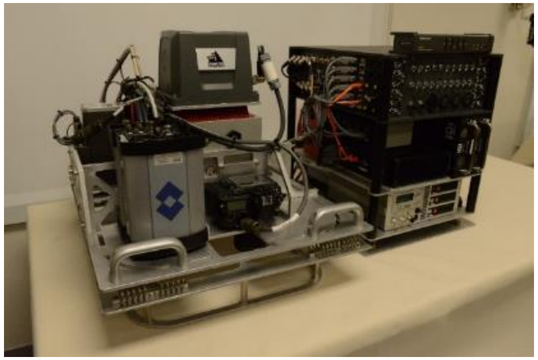
review recent scientific advances made possible by measurements acquired using a unique **combination of remote sensing platforms, in-situ and laboratory observational approaches**.



SIO Modular Aerial Sensing System (MASS)

- The MASS is a **mature and proven** portable package of high-resolution instrumentation built specifically for airborne remote sensing applications.
  - Over 1300 hours of accumulated flight time over the course of more than **35 different field campaigns.**
  - Successfully operated from a broad range of aircraft (Cessna 206, Partenavia P-68, Gulfstream-V and DHC-6 Twin Otter) as well as from a Bell 206 helicopter.
  - Two MASS systems currently in operation.

- MASS data are used to provide measurements of:
  - Ocean waves
  - Currents
  - Stokes drift
  - Sea surface height (SSH)
  - Ocean transport and dispersion
  - Biological activity
  - Hydrological and terrestrial applications include measurements of snow cover, coastal geomorphology, and the built environment



US Army Corps of Engineers
SERDP DOD · EPA · DOE
ESTCP
Naval Information Warfare Center ATLANTIC
JPL Jet Propulsion Laboratory California Institute of Technology
erc European Research Council

SIO Modular Aerial Sensing System (MASS)

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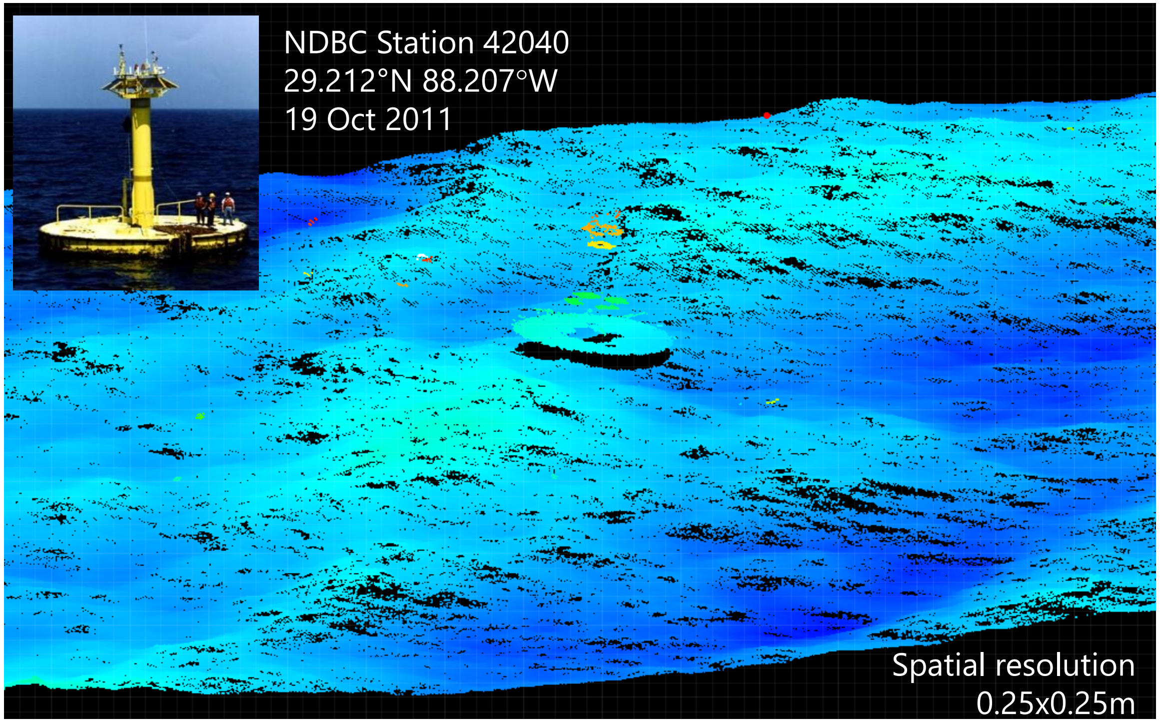
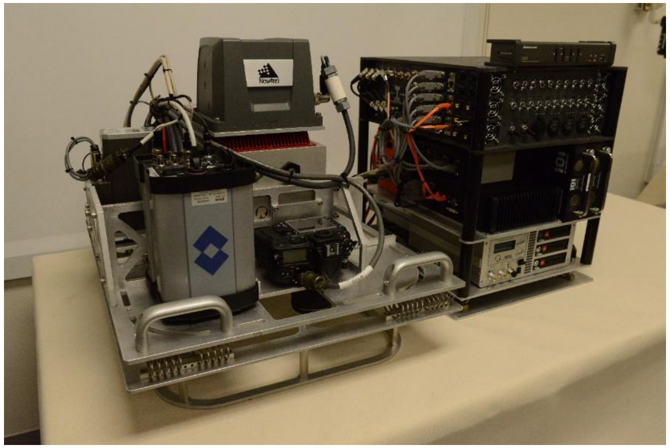


Example of surface elevation as measured from the MASS during a 2011 experiment in the Gulf of Mexico, flying above NDBC buoy #42040. (wind~12m/s, Hs = 3.1m)



Instrumentation	**Measurement**	
Scanning Waveform Lidar	Riegl many models	Surface wave, surface slope, directional wave spectra (vert. accuracy ~2-3cm)
Long-wave IR Camera	FLIR Many models	Ocean surface processes, wave kinematics and breaking, frontal processes
High-Resolution Video	Many models	Ocean surface processes, wave kinematics and breaking, frontal processes
Hyperspectral Camera	Specim Kestrel	Ocean surface and biogeochemical processes
GPS/IMU		Georeferencing, trajectory
DoppVis (Lenain et al . 2023)		**Surface currents, vertical shear, wave breaking statistics**

Directional wave measurements down to sub-meter scales

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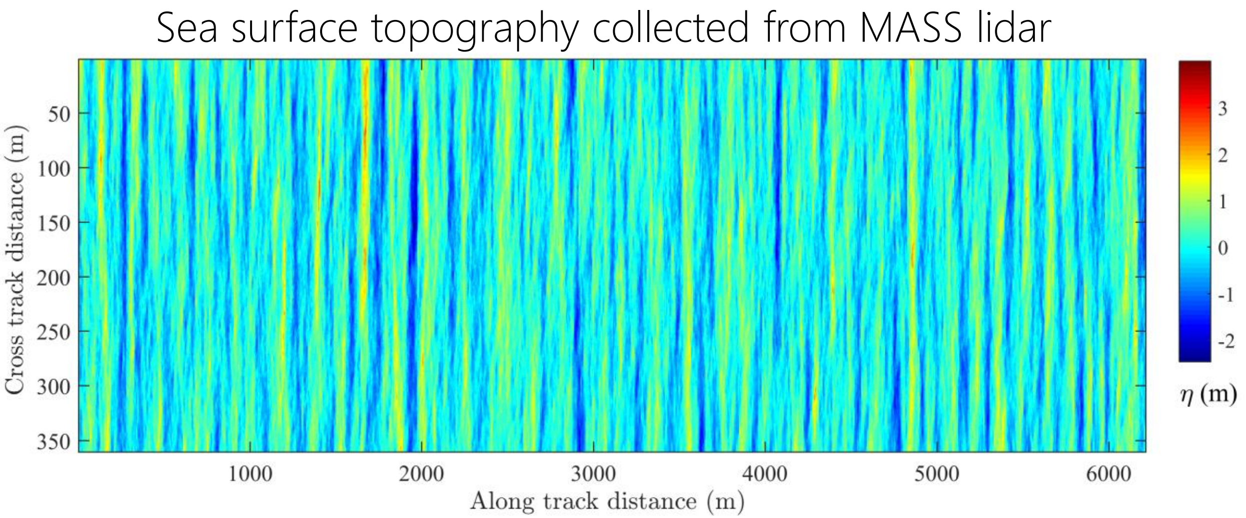
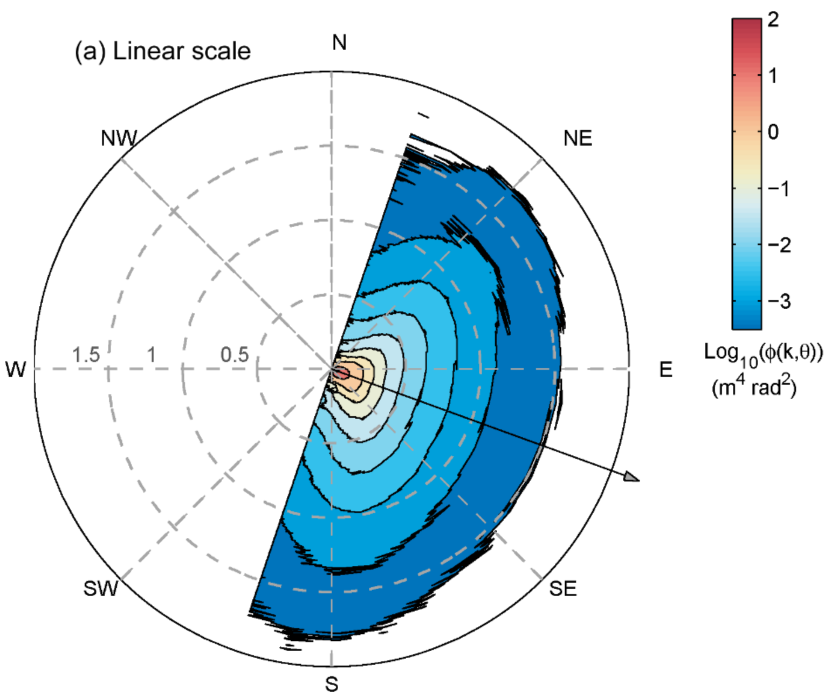
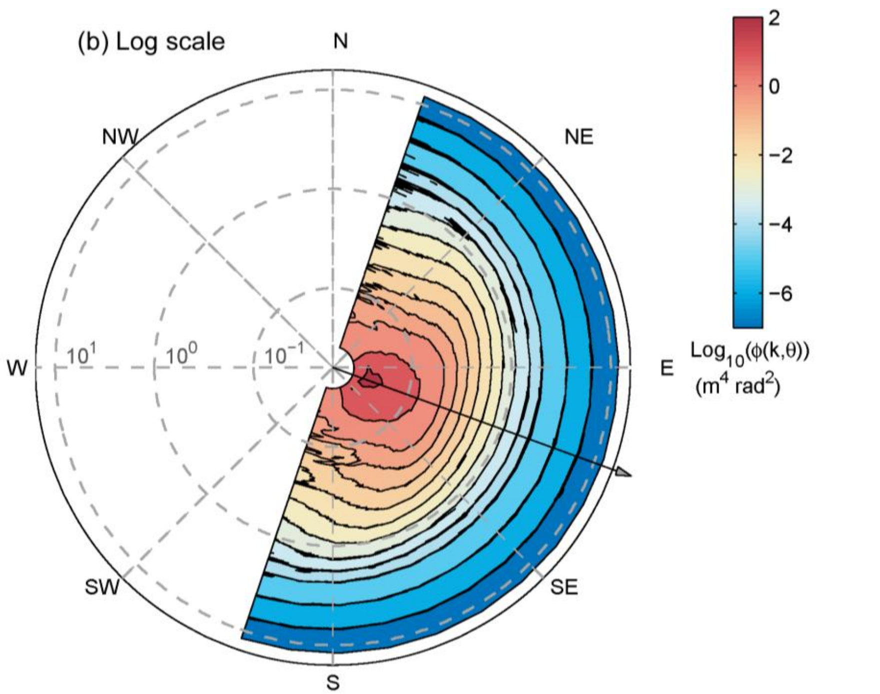
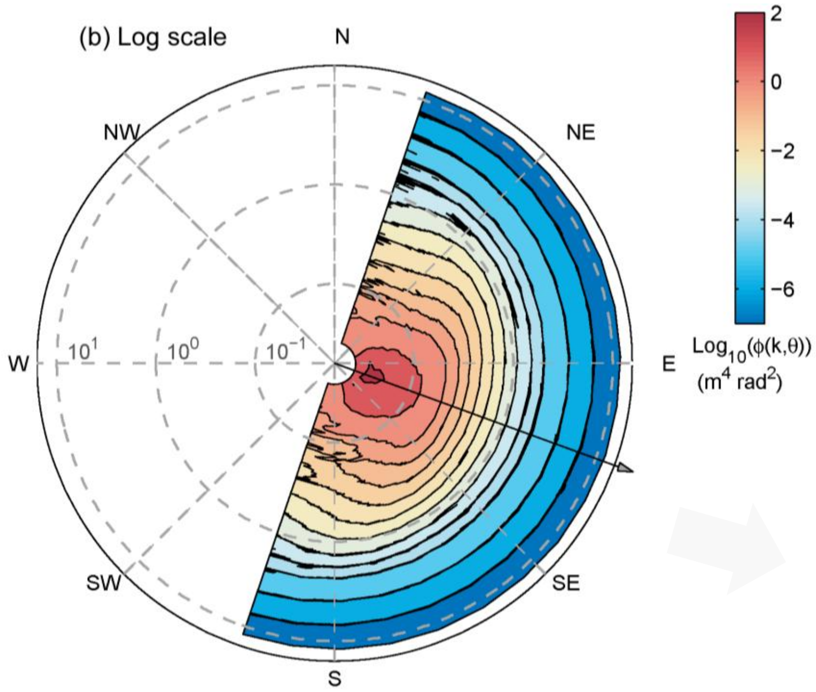


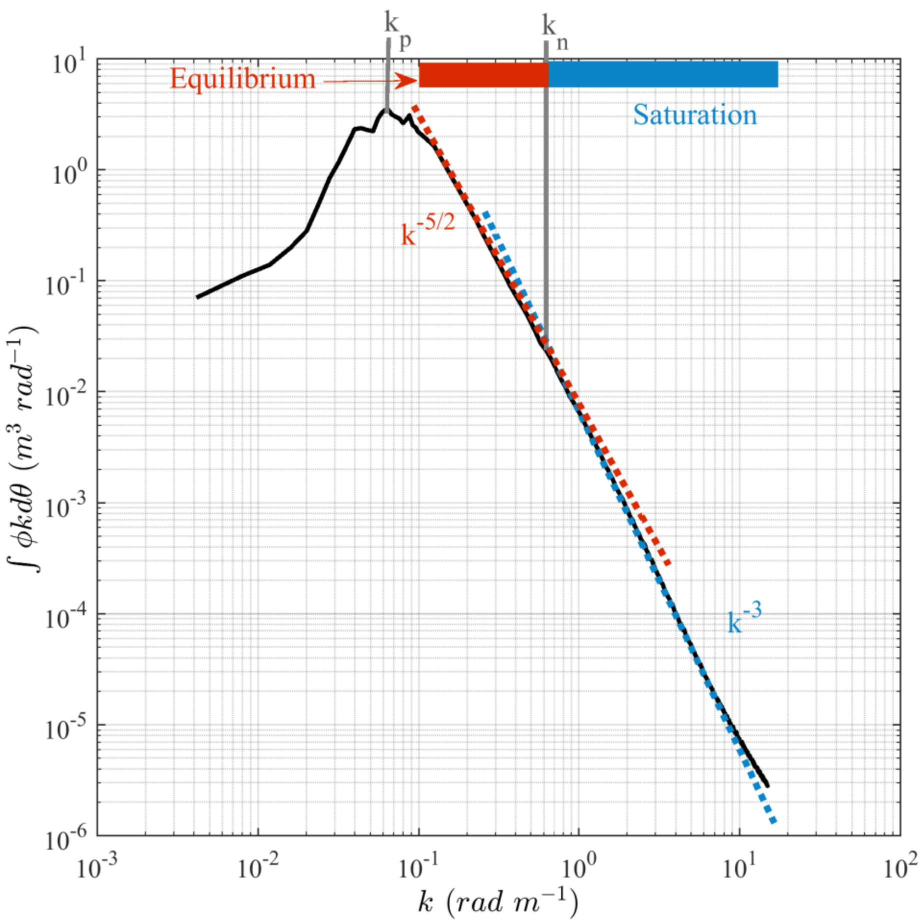




Lenain & Melville (2017, JPO)

Example of omnidirectional wavenumber spectrum





Consistent with Phillips (1985) equilibrium model and our understanding of the saturation range

Lenain & Melville (2017, JPO)

Parameterizing the Equilibrium-Saturation range transitions

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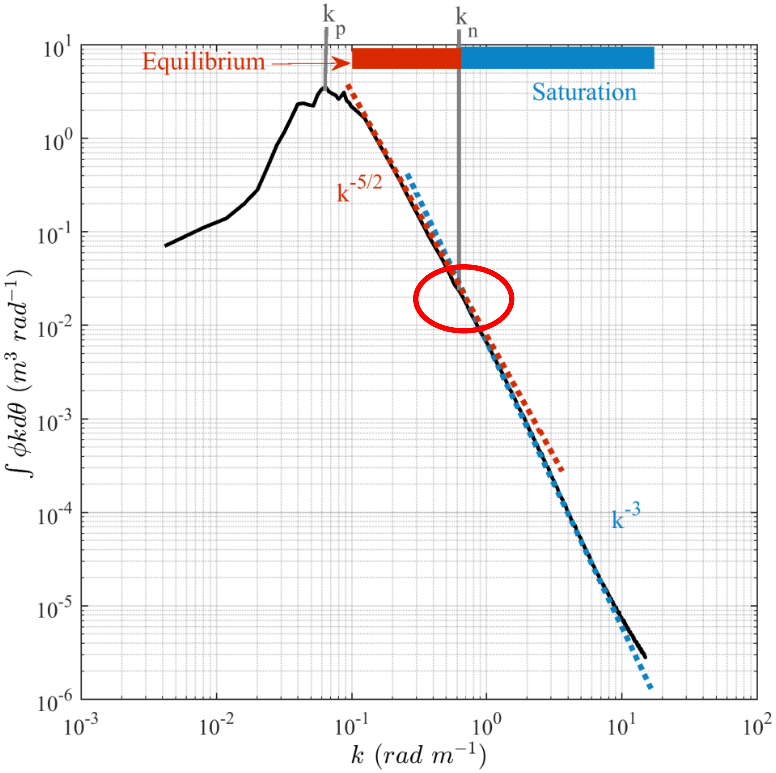


Wave spectrum

↓

Stokes drift

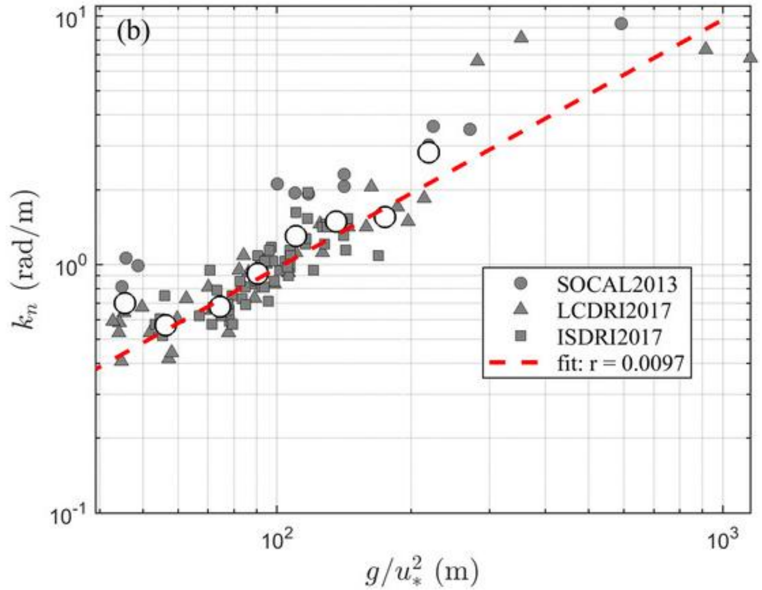
↓

Langmuir turbulence number

↓

Upper ocean mixing!

u_* :atmospheric friction velocity



Fitting equilibrium and saturation ranges to determine intersect point located at k_n

Consistent with Phillips (1985)

$$r = \frac{k_n u_*^2}{g}$$

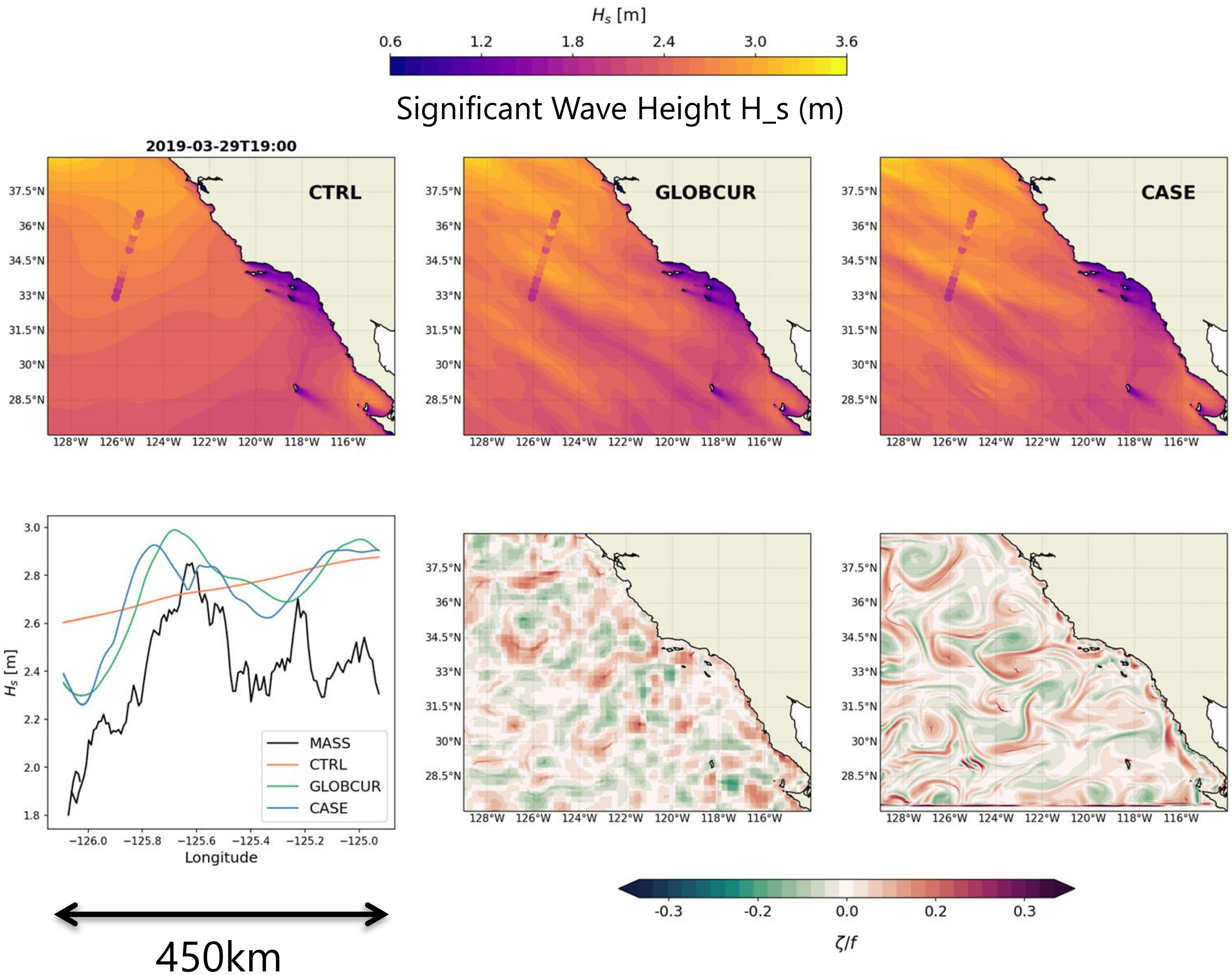
Crucial for wind-wave modelling and upper ocean studies (i.e. Stokes drift requires accurate depiction of the spectral shape across the equilibrium-saturation ranges)

Lenain & Pizzo (2020, JPO)

Wave interacting with currents

Currents modulate the properties of surface gravity waves through:

- **wave refraction** (e.g. Ardhuin et al. 2017, Romero et al. 2017, 2020, Villas Bôas et al. 2020)
- **local effects** (Rascle et al. 2016, Lenain & Pizzo 2021, Vrecica et al. 2022, Lenain et al. 2023)



- Without currents the model completely misses the spatial variability of Hs at meso large submesoscales
- Lots of submesoscale Hs observed variability not captured in the model**. We need high-resolution currents! (e.g. DoppVis)**

WaveWatch III simulations run by Bia Villas Boas (Colorado School of Mines)

Local effects: Gulf Stream wave-current interaction (CASPER MURI, 2015, PC: D. Khelif)

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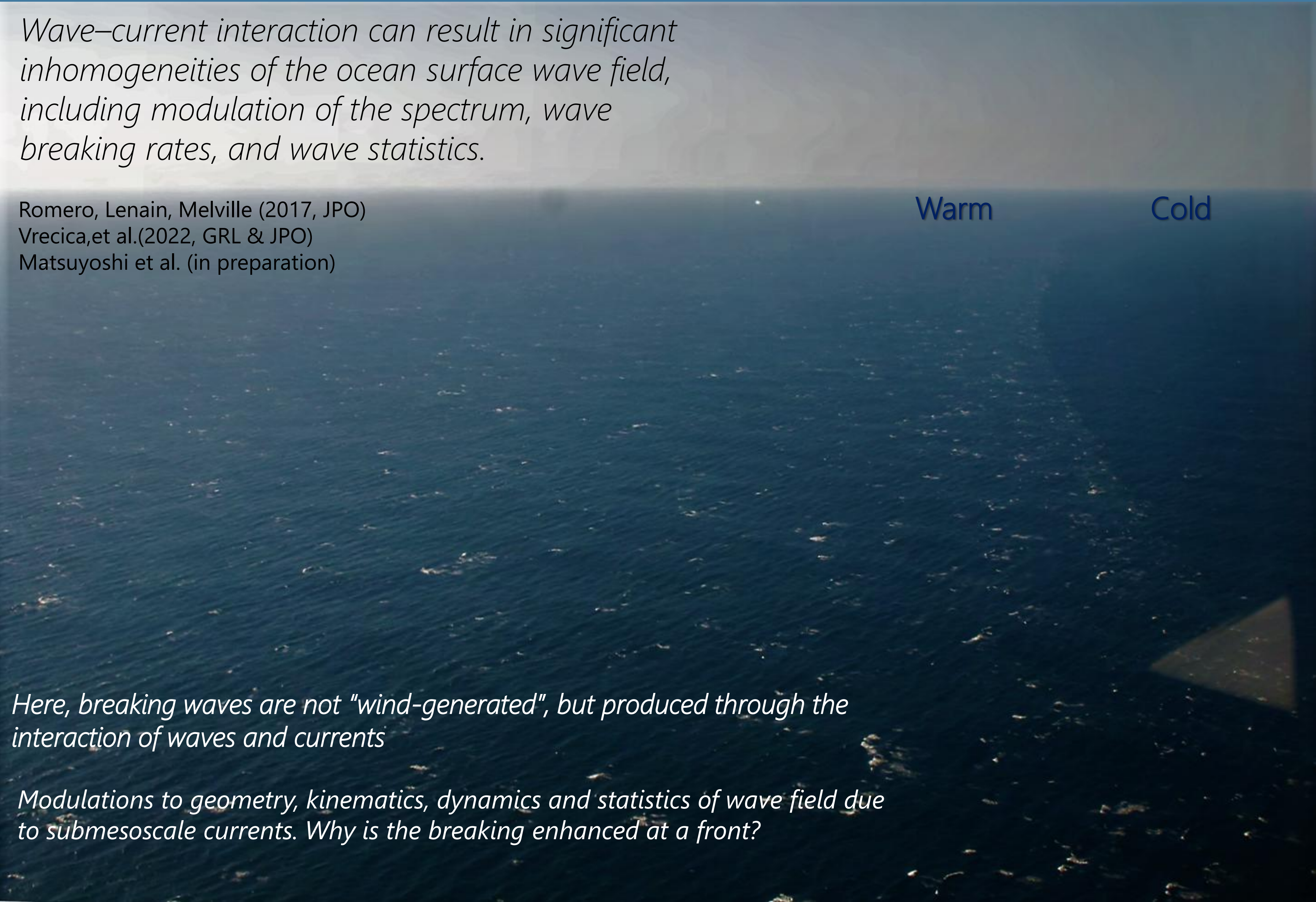
Wave–current interaction can result in significant inhomogeneities of the ocean surface wave field, including modulation of the spectrum, wave breaking rates, and wave statistics.

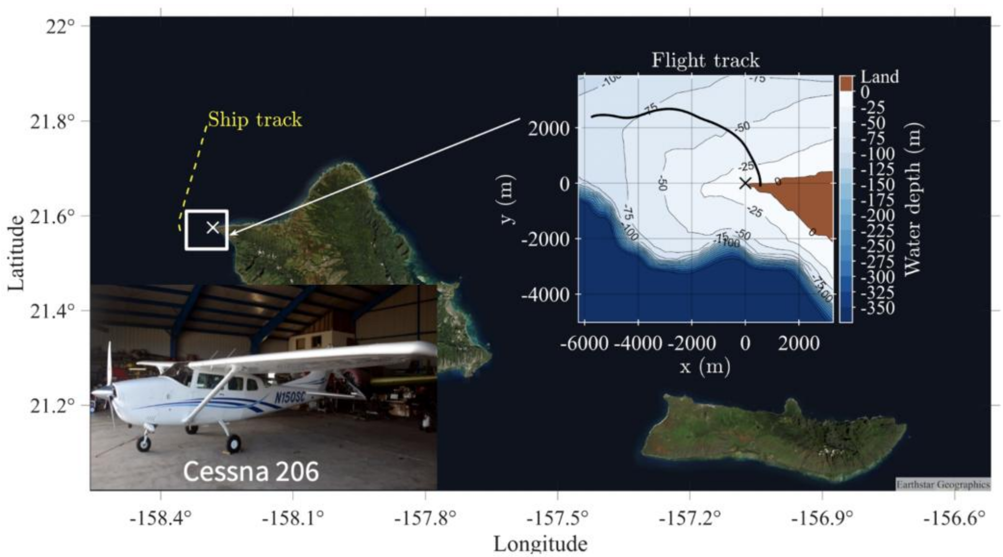
Romero, Lenain, Melville (2017, JPO)
Vrecica,et al.(2022, GRL & JPO)
Matsuyoshi et al. (in preparation)

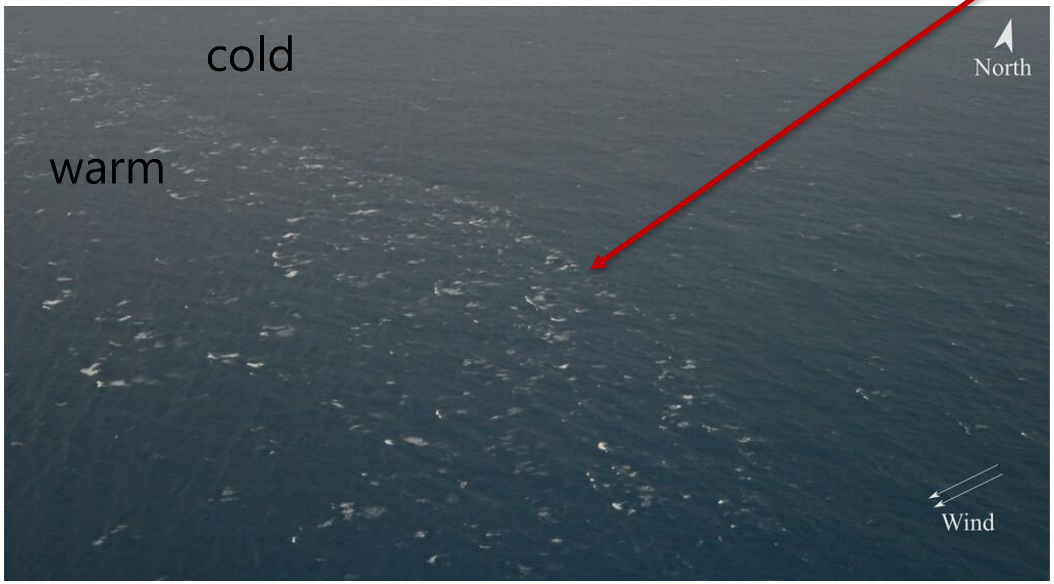


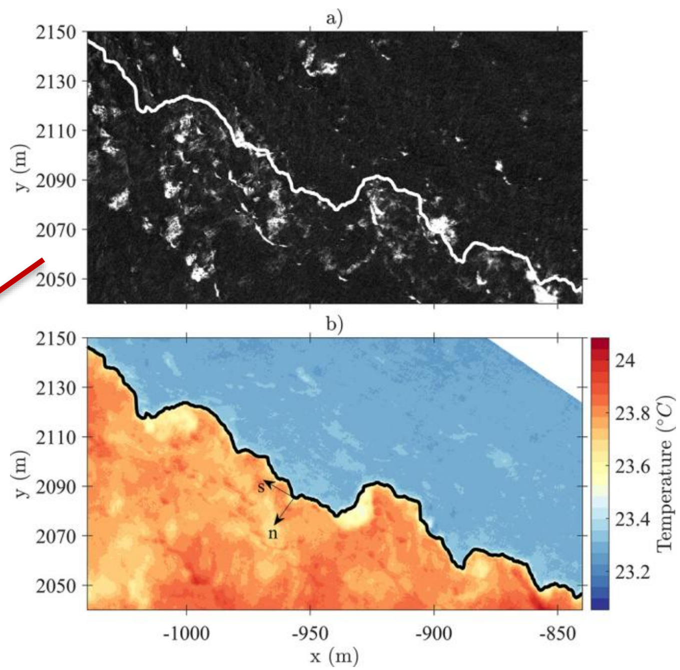
Here, breaking waves are not "wind-generated", but produced through the interaction of waves and currents

Modulations to geometry, kinematics, dynamics and statistics of wave field due to submesoscale currents. Why is the breaking enhanced at a front?

Modulation of Surface Gravity Waves at a Submesoscale Front







Vrecica et al. (2022, JPO)

Modulation of Surface Gravity Waves at a Submesoscale Front

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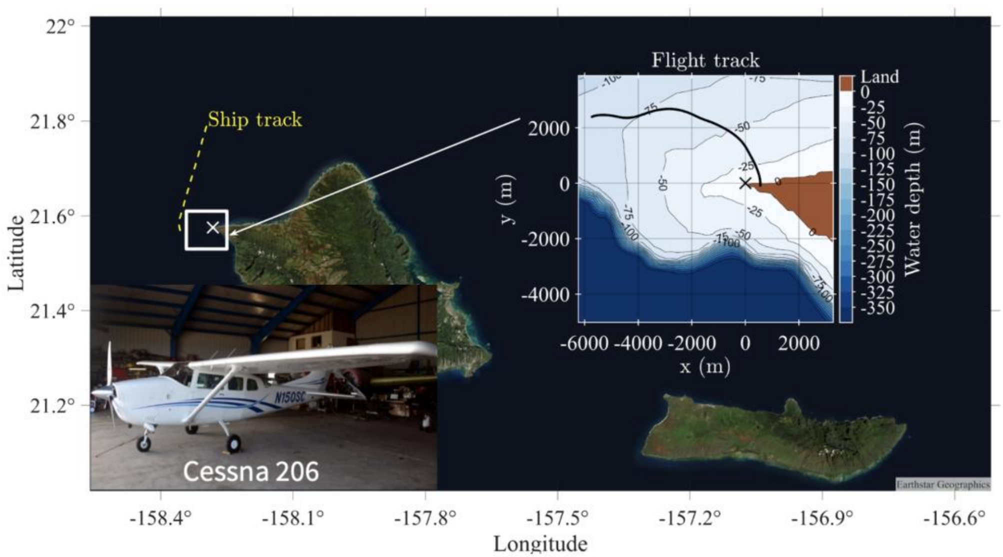
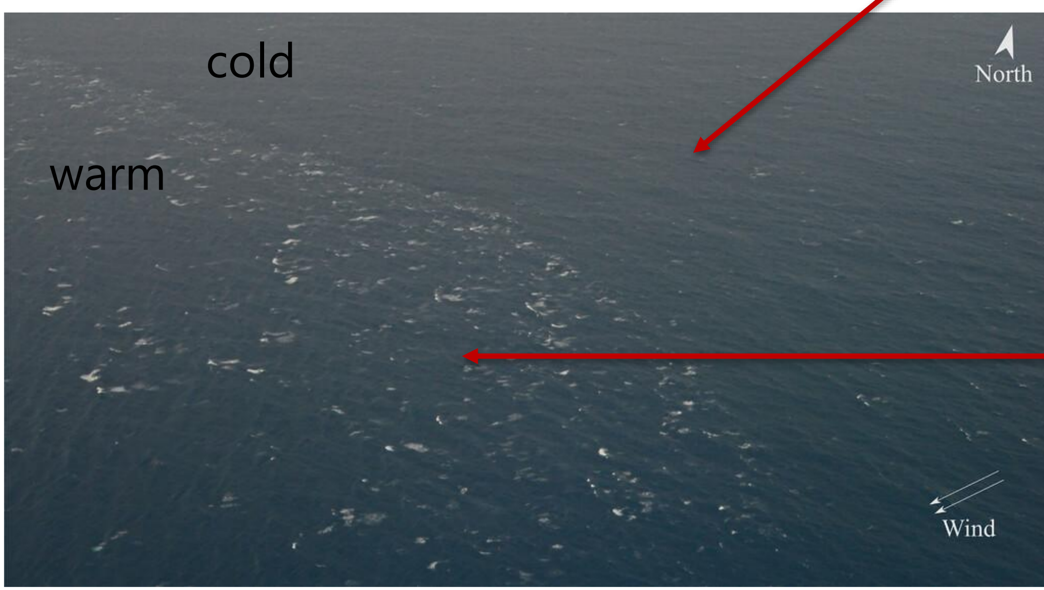
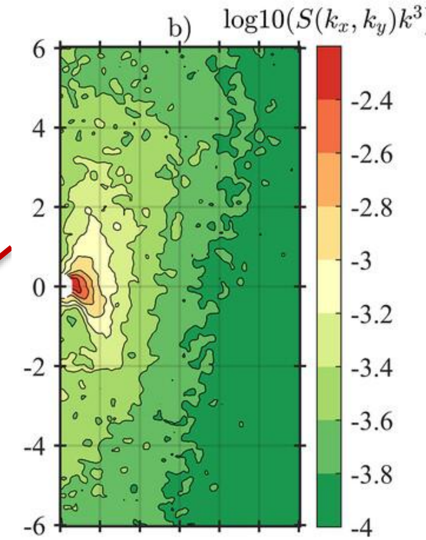
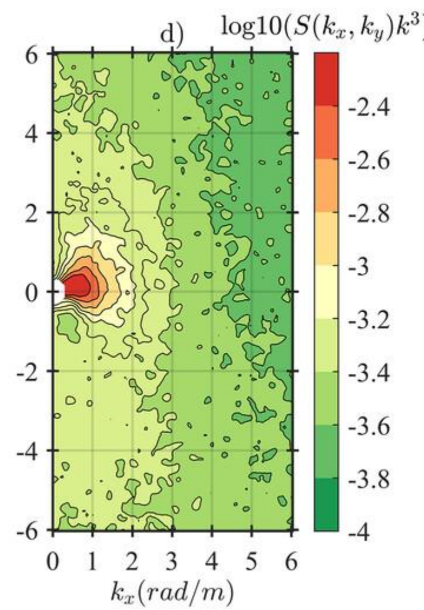




Directional Wave Saturation Spectra





Vrecica et al. (2022, JPO)

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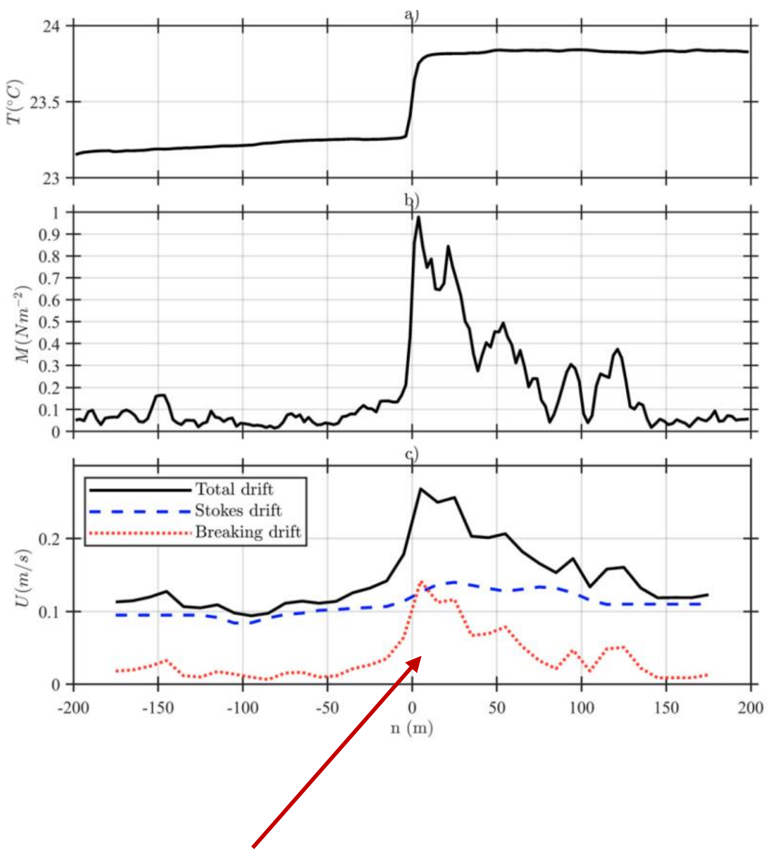
SST

Momentum due to wave breaking going into the ocean

fourth moment of $\Lambda(c)$ distribution – see Phillips (1985)

drift



Significant contribution of wave-breaking induced momentum (and non-uniform)

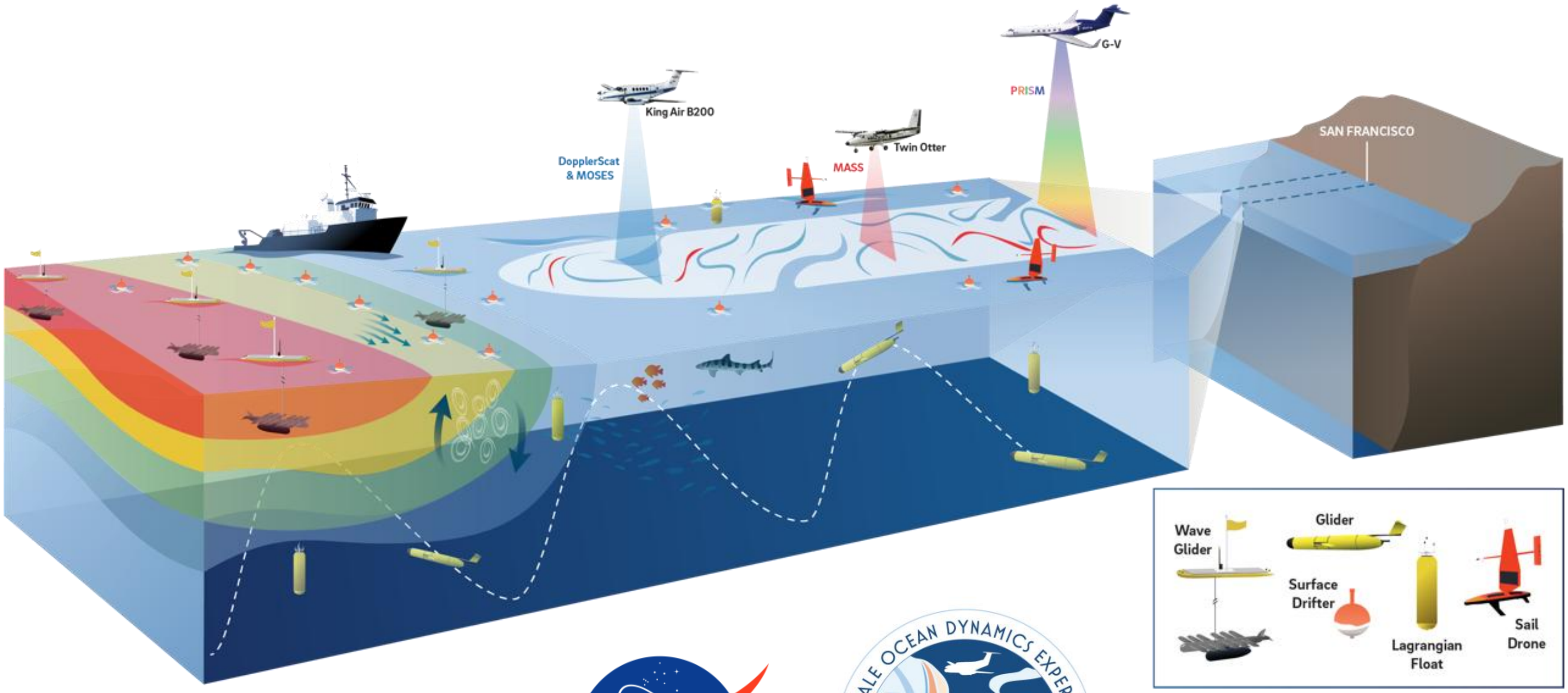
What are the dynamical consequences of this additional transport on the submesoscale?

Vrecica et al. (2022, JPO)

NASA S-MODE program

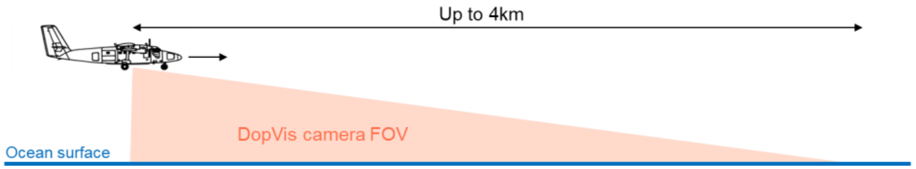
To characterize the contribution of the submesoscale ocean dynamics to vertical exchange of climate and biological variables in the upper ocean

Our understanding of the role played by ocean surface waves and breaking in submesoscale dynamics as well as the **feedback to and from the atmosphere** at the scale of fronts and filaments, is very limited.

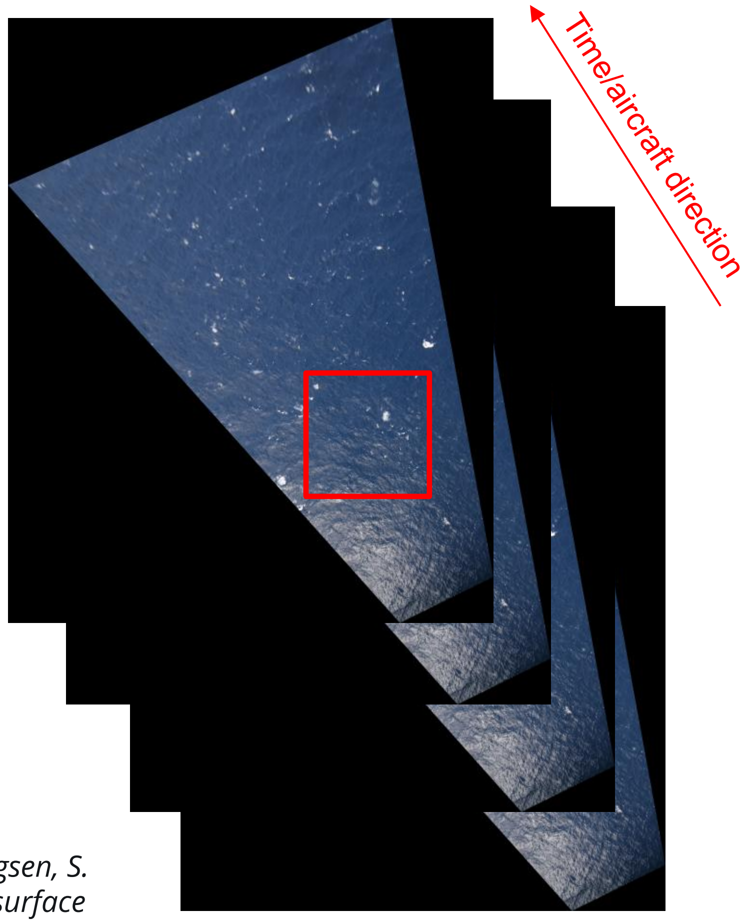


MASS DoppVis instrument

DoppVis instrument concept: Capturing upper-ocean current profiles (first few meters) along the track of the aircraft through observations of the spatio-temporal evolution of surface waves (**dispersion relationship method**), following the work of Dugan et al. (2001) and more recently the Fugro ROCIS team.



"Stack" georeferenced images together to identify overlapping region (256x256m squares)



Lenain, L., Smeltzer, B. K., Pizzo, N., Freilich, M., Colosi, L., Ellingsen, S. Å., et al. (2023). Airborne remote sensing of upper-ocean and surface properties, currents and their gradients from meso to submesoscales.

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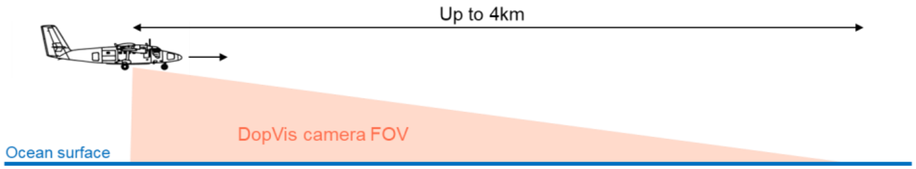
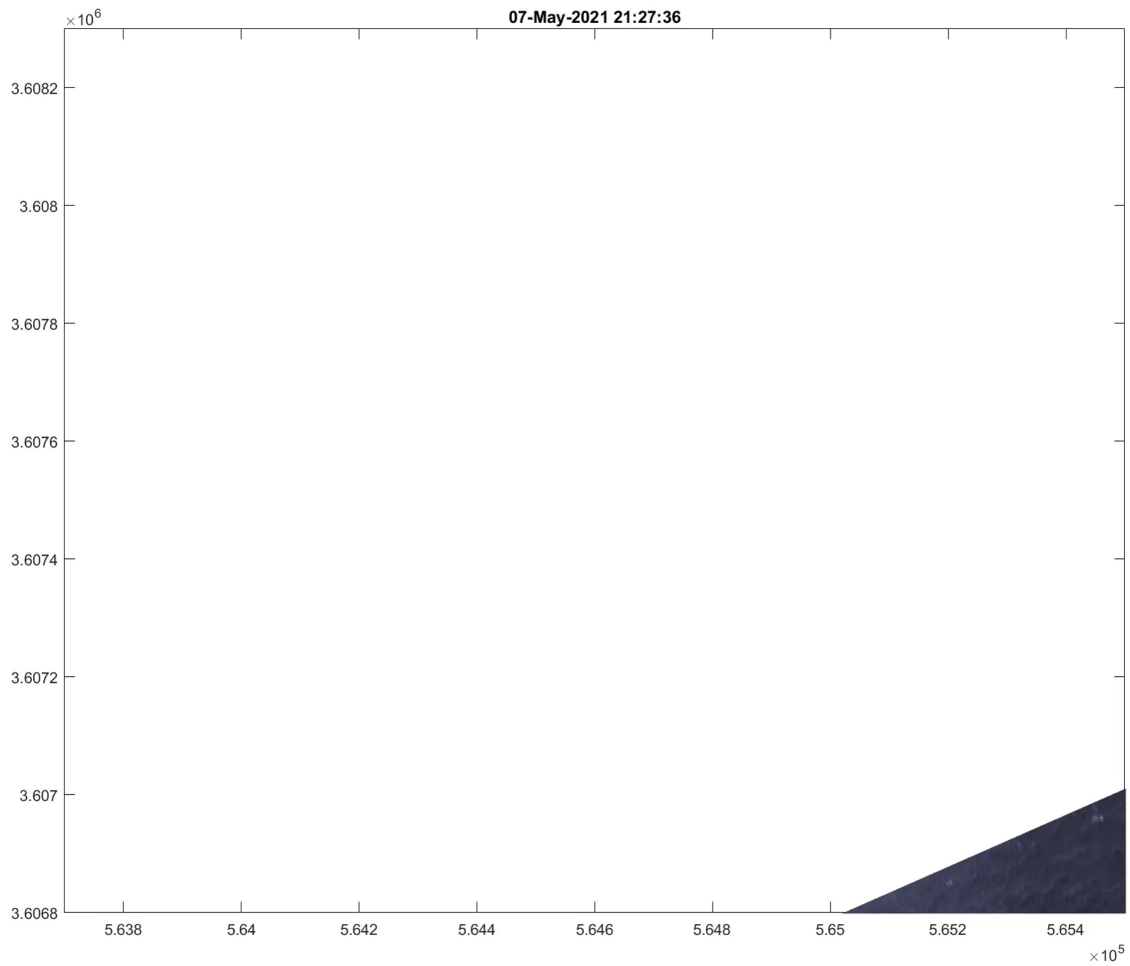
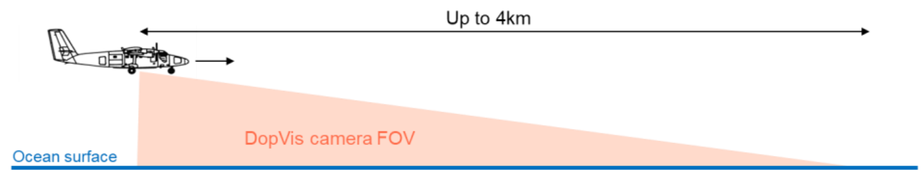
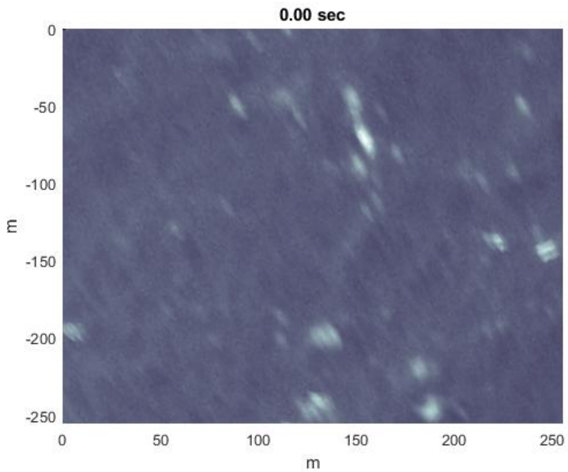




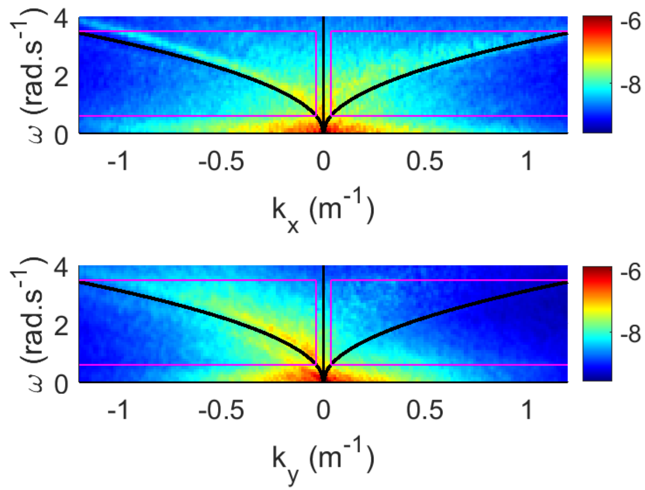
MASS DoppVis surface currents (Lenain et al. 2023)

DoppVis instrument concept: Capturing upper-ocean current profiles (first few meters) along the track of the aircraft through observations of the spatio-temporal evolution of surface waves (**dispersion relationship method**), following the work of Dugan et al. (2001) and more recently the Fugro ROCIS team.





3D Spectra



Invert for upper ocean currents and shear (vertical and horizontal)

Horizontal resolution: 128-1000m
Depth range: 0.5-3m (wave conditions dependent)

Lenain, L., Smeltzer, B. K., Pizzo, N., Freilich, M., Colosi, L., Ellingsen, S. Å., et al. (2023). Airborne remote sensing of upper-ocean and surface properties, currents and their gradients from meso to submesoscales.

Combining SST and DoppVis surface currents

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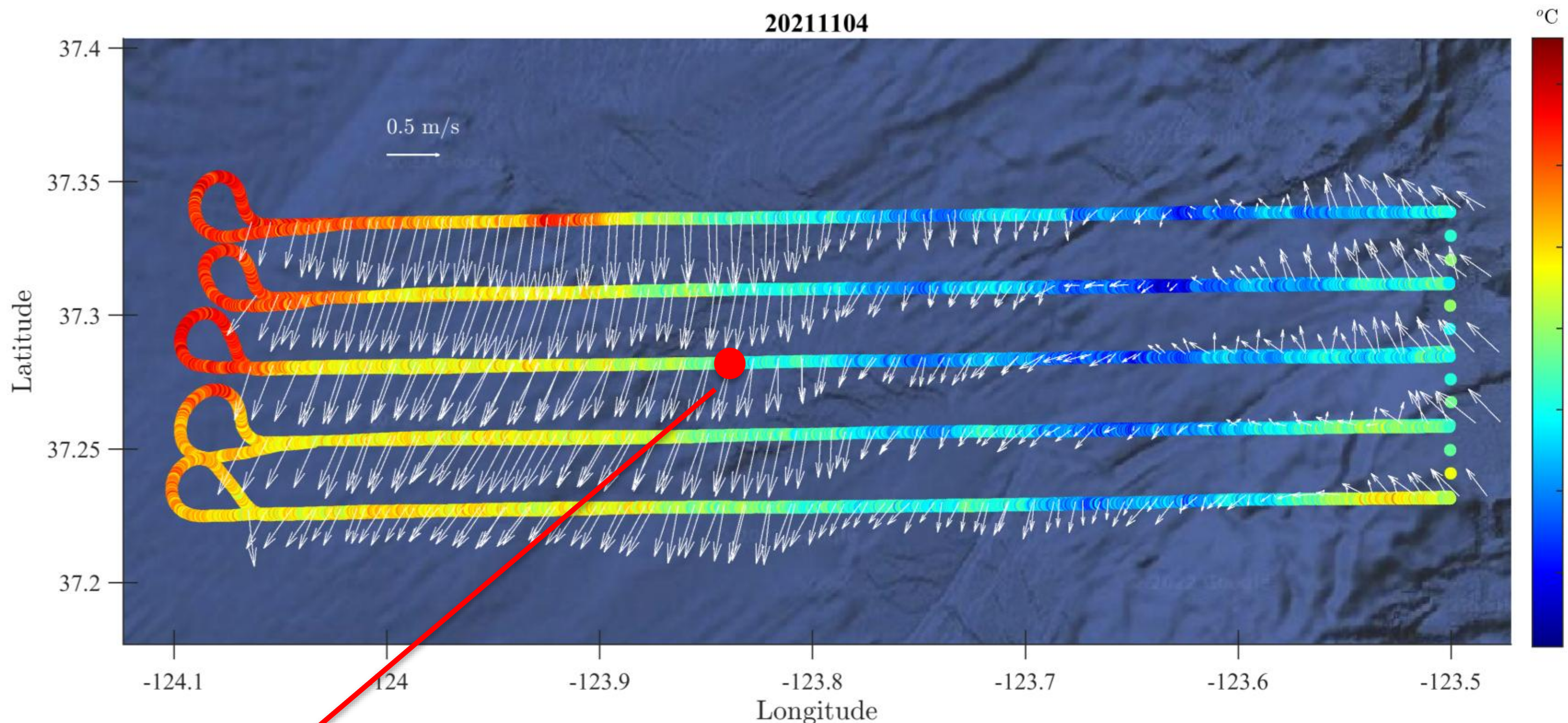
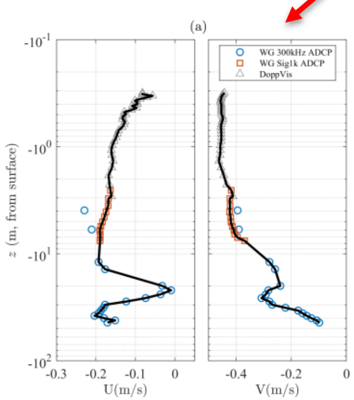
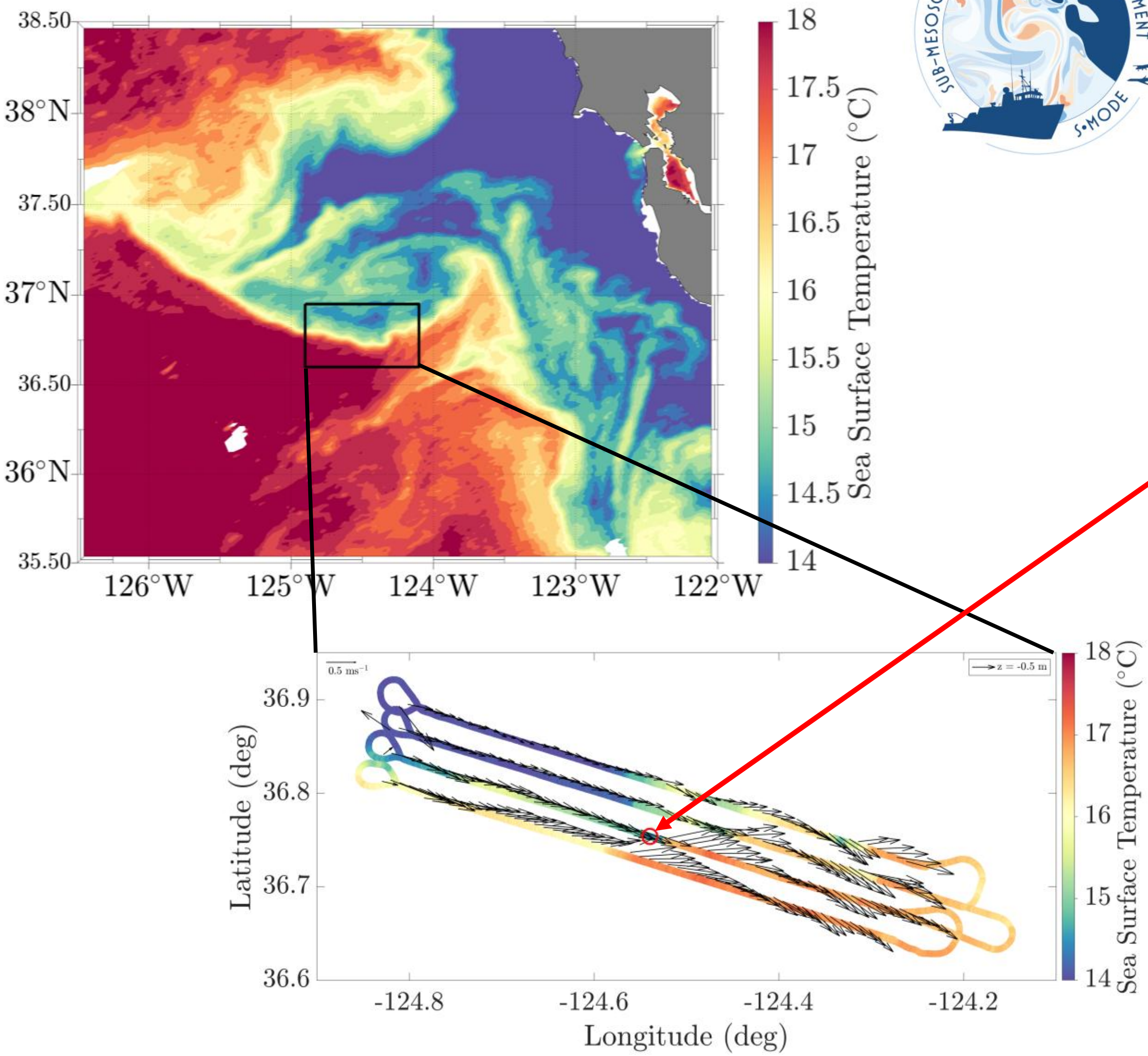




Map of depth integrated near surface currents (1km along-track resolution)

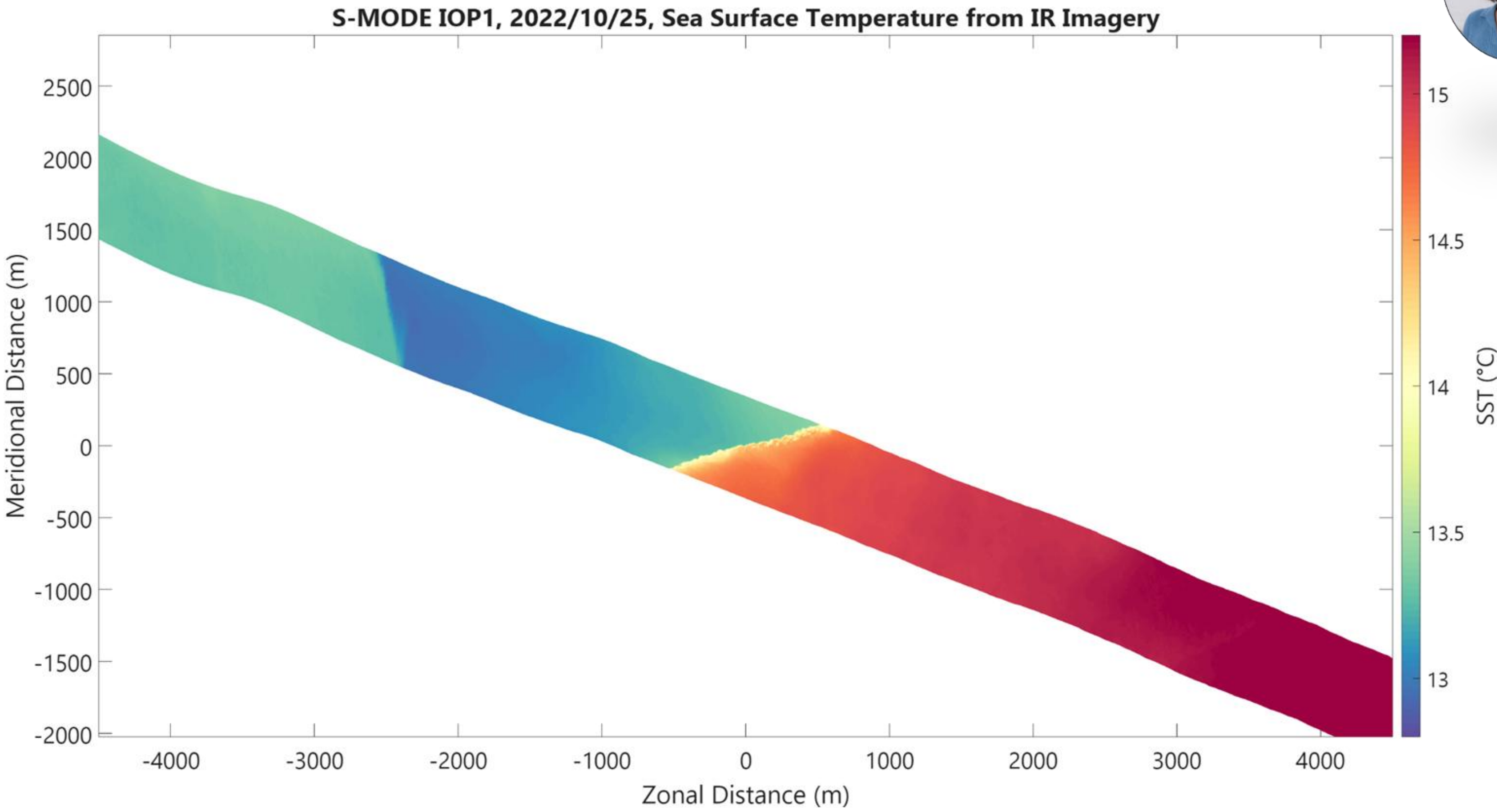
Exploring the role of submesoscale current variability on wave spectral properties



Enhanced wave breaking is observed at the frontal boundary suggesting modulation of surface waves by currents.

SST imagery section across a sharp front

Kayli Matsuyoshi (SIO PhD)



Combining SST and DoppVis currents

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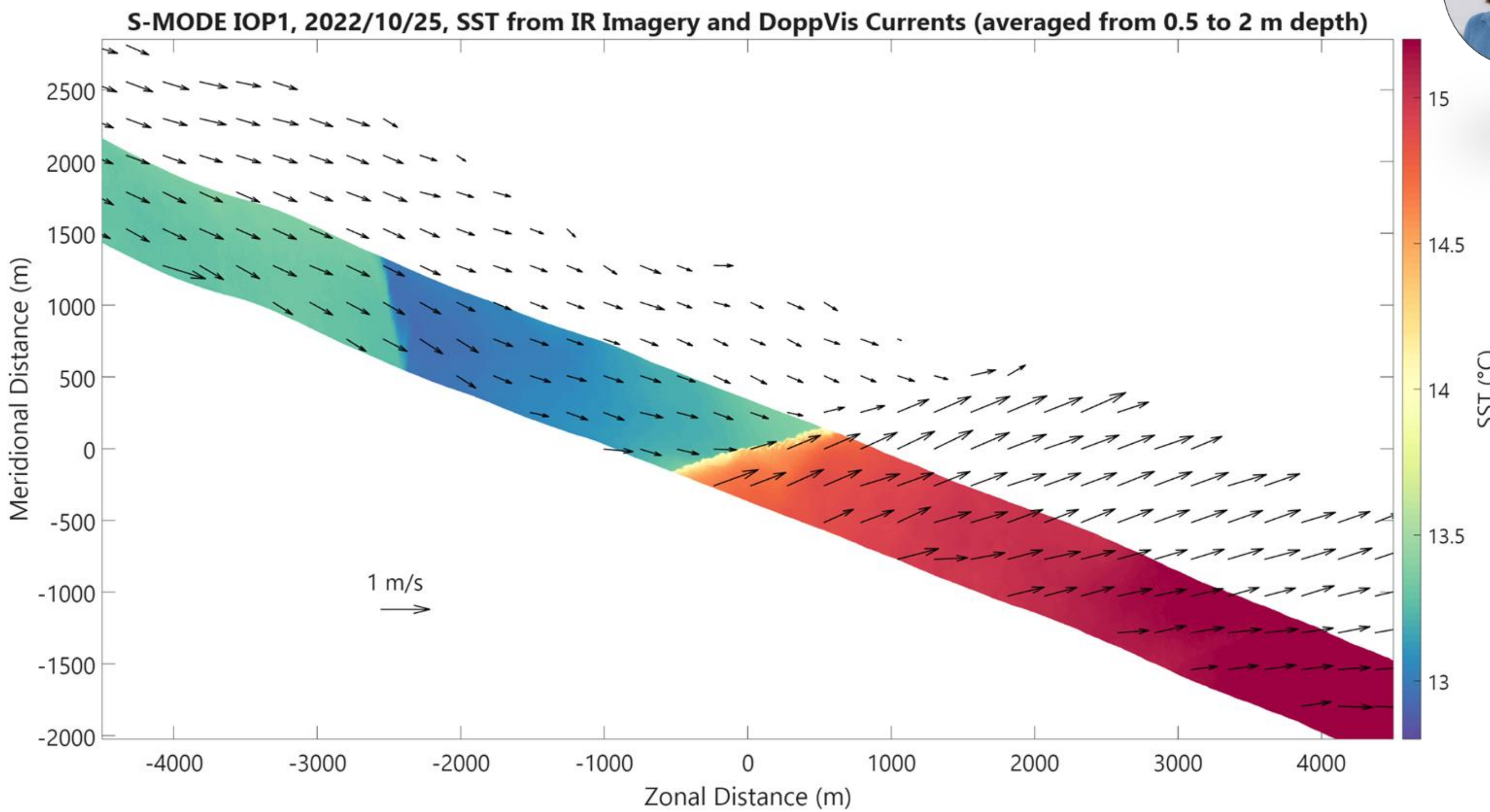

Combining SST and DoppVis currents

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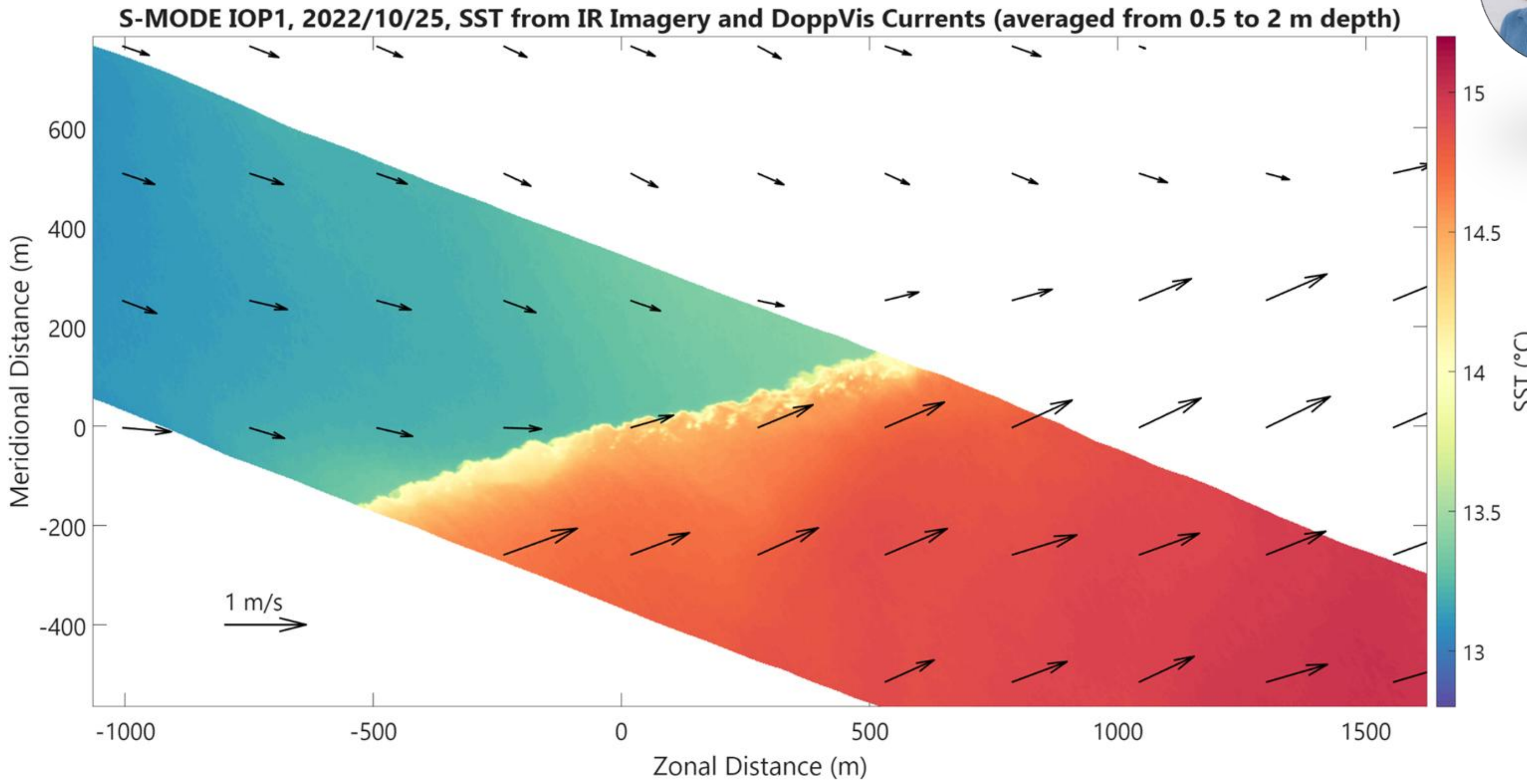

Hyperspectral imagery

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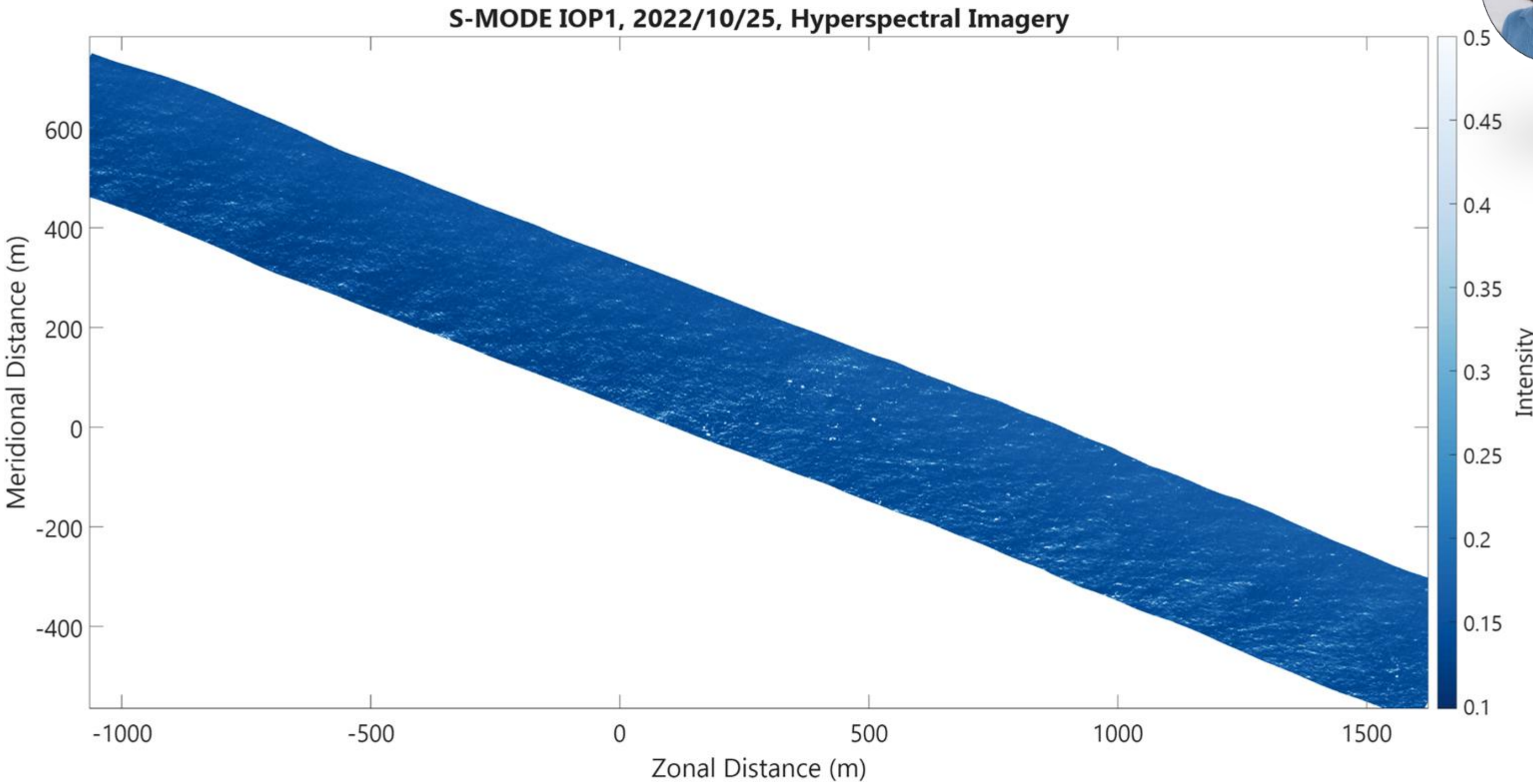
Kayli Matsuyoshi (SIO PhD)



Hyperspectral imagery

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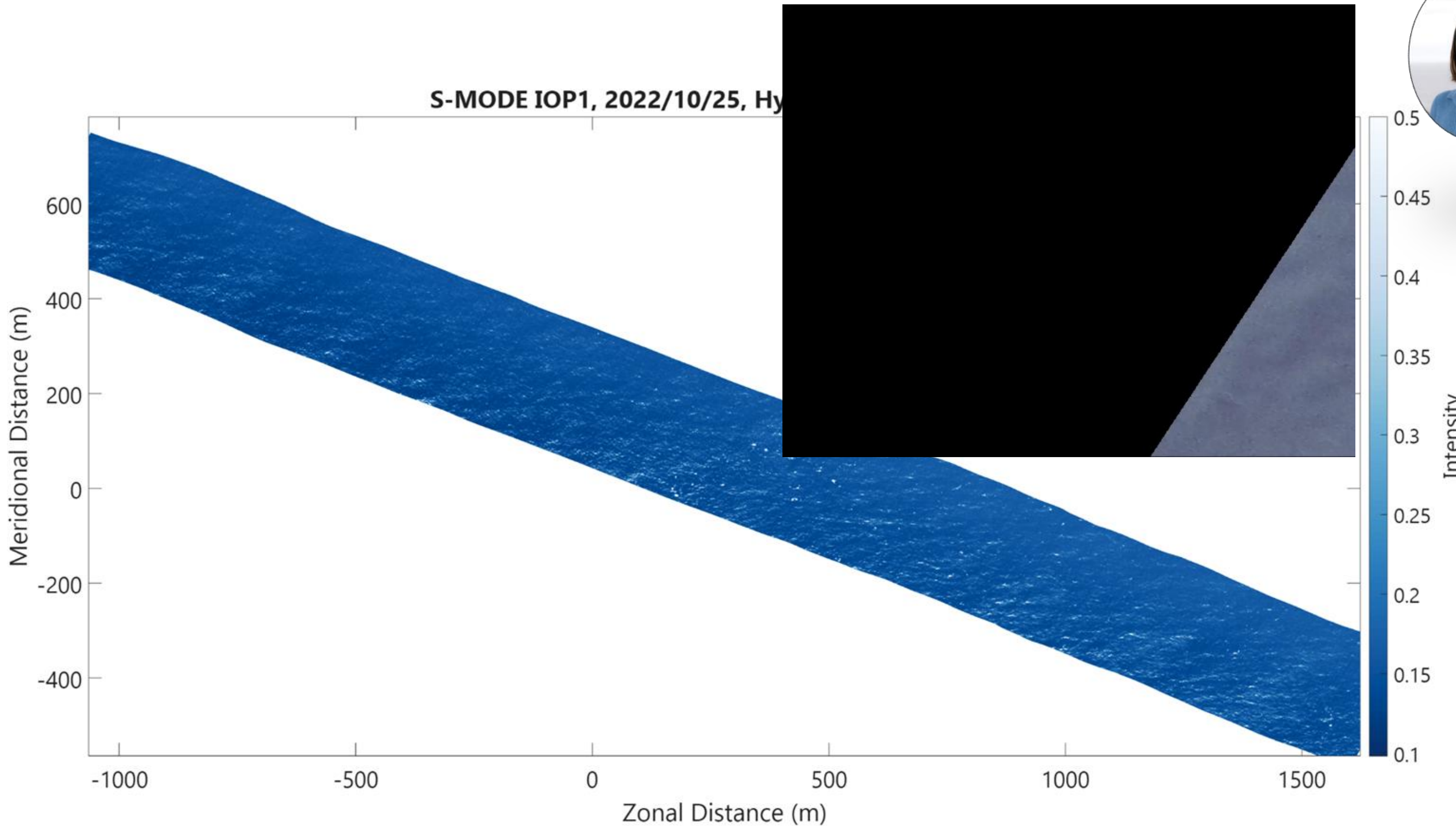
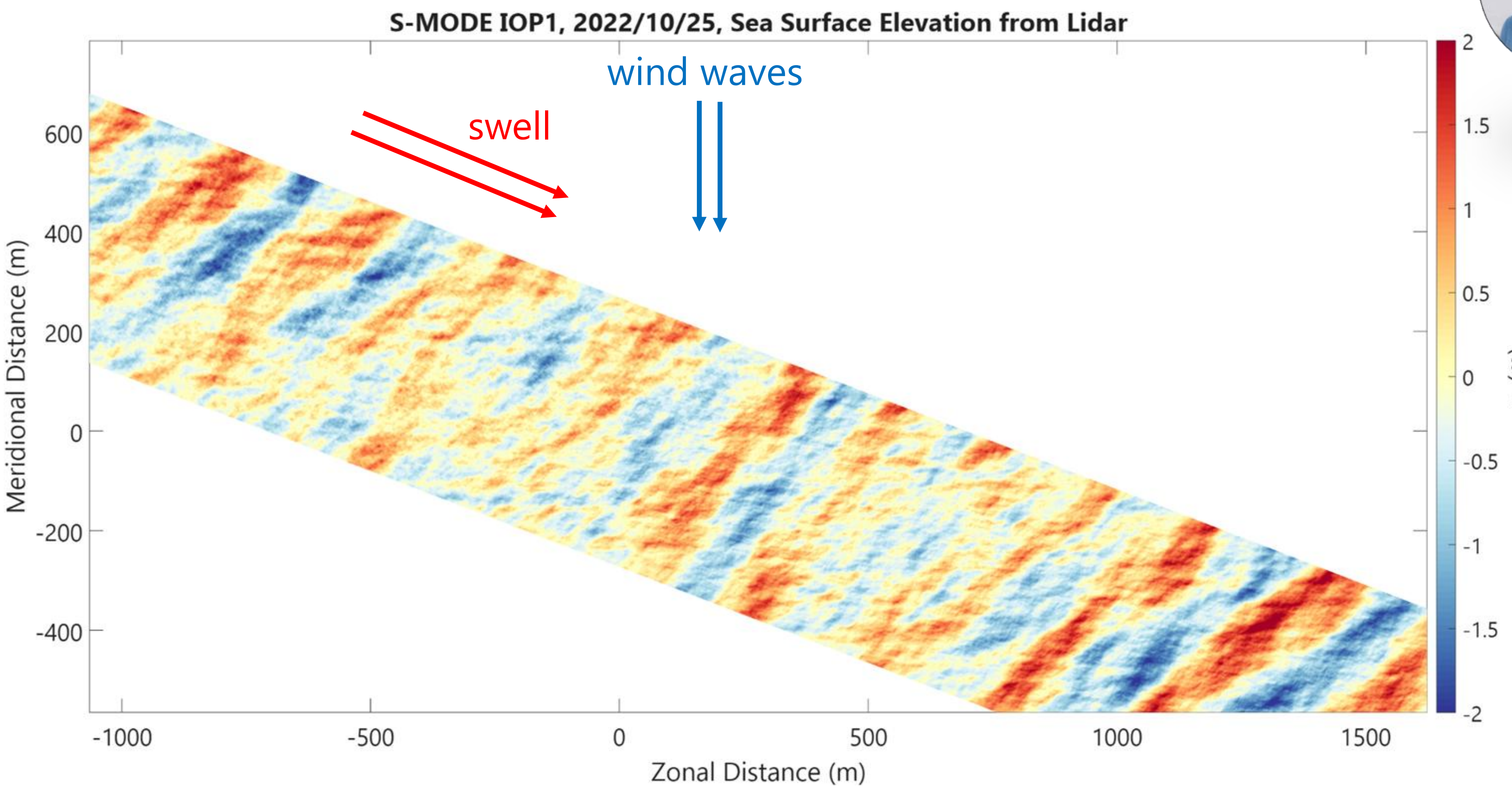


Surface waves measured from the MASS lidar

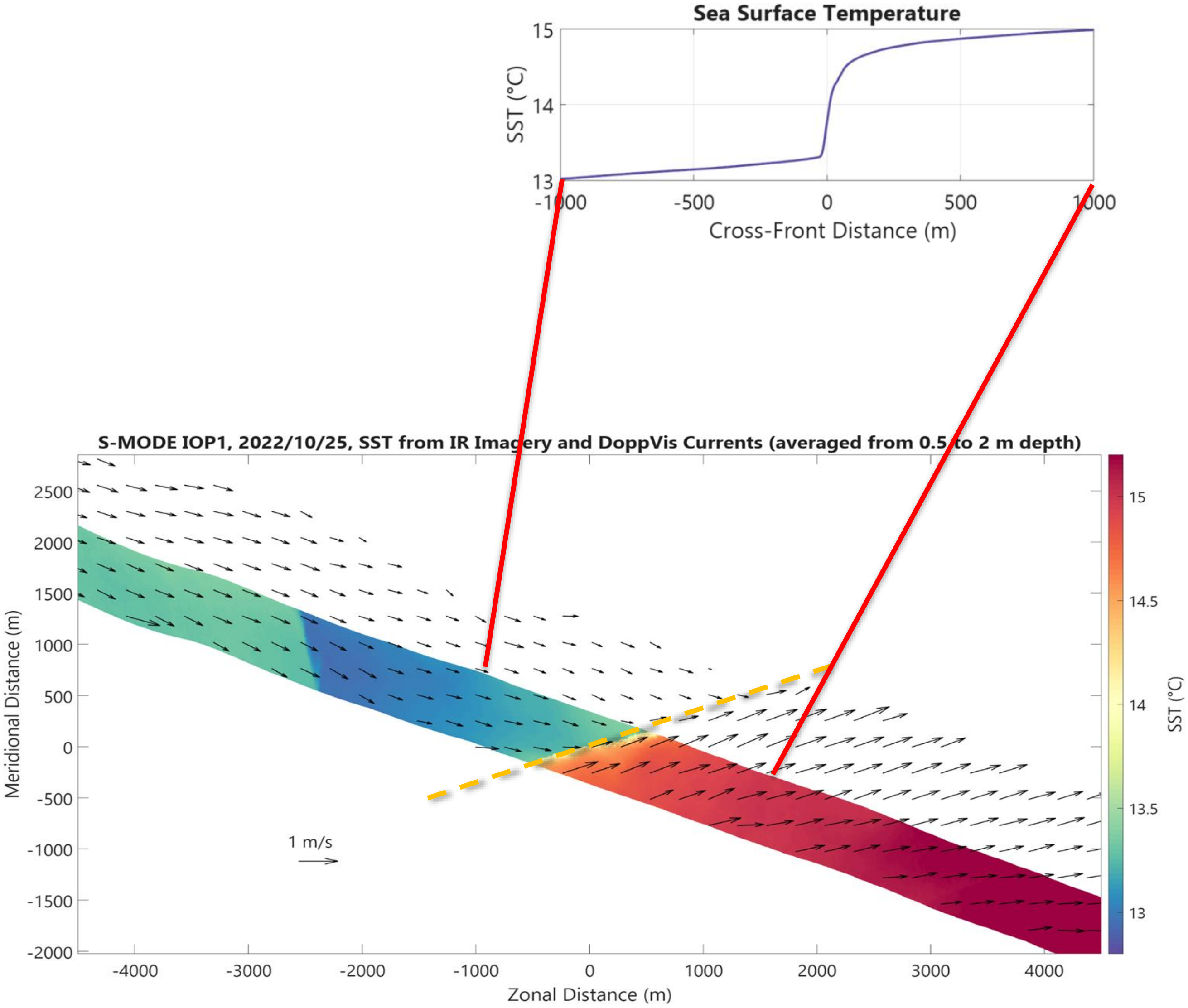
Scripps Institution of Oceanography UC San Diego

Kayli Matsuyoshi (SIO PhD)



Integrating in the along-front direction

Kayli Matsuyoshi (SIO PhD)



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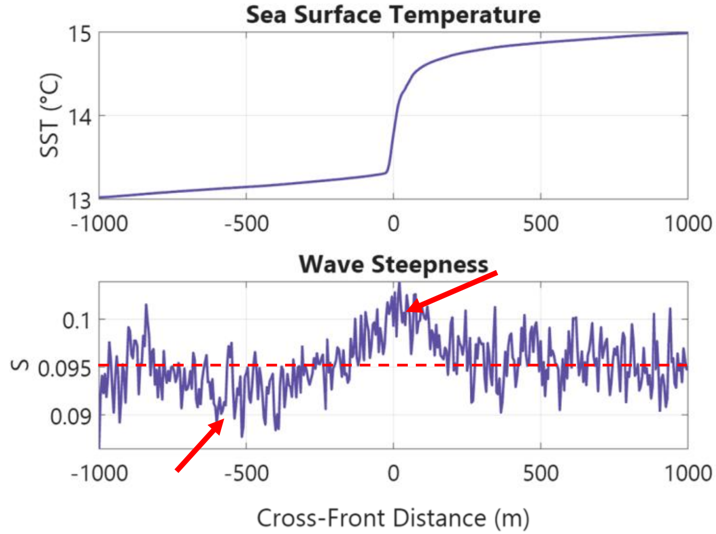

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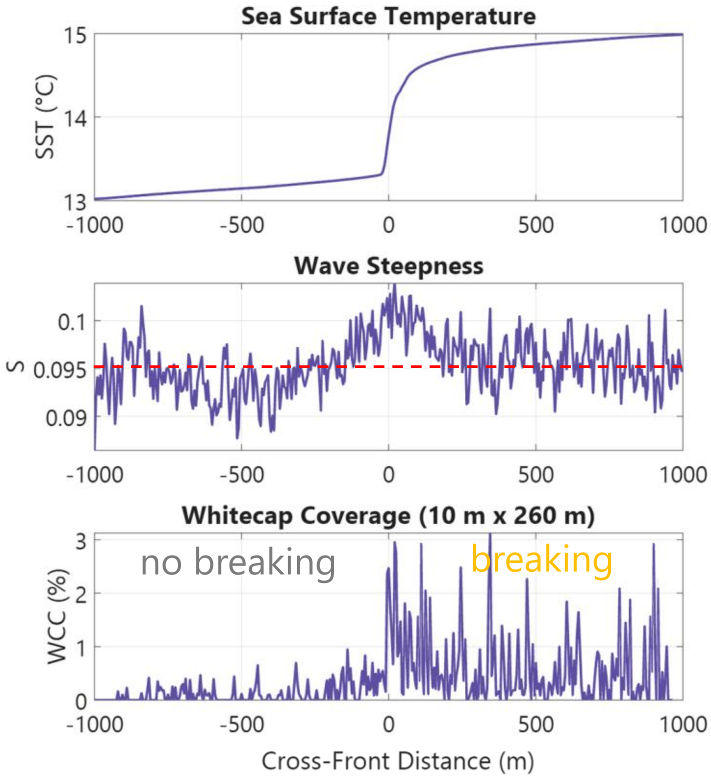

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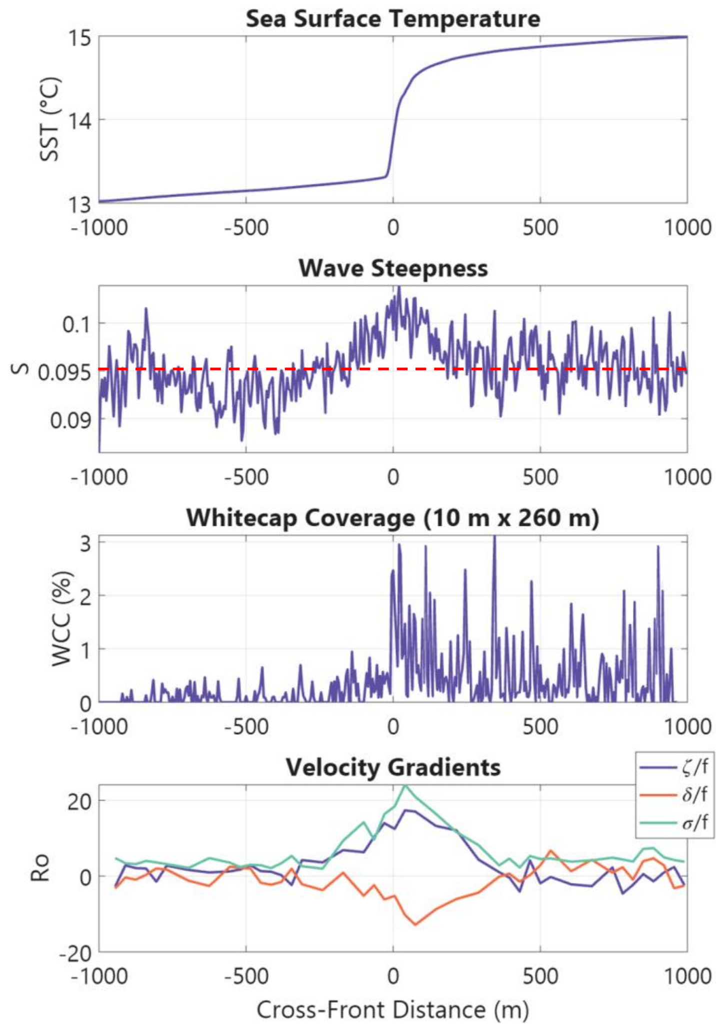

Divergence ~10*f* at the front!!

Summary

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- Recent progress advancing our ability to characterize air-sea interaction processes and ocean dynamics from mesoscale to submesoscale (and smaller) achieved through the development of novel laboratory, airborne and in-situ observational techniques.

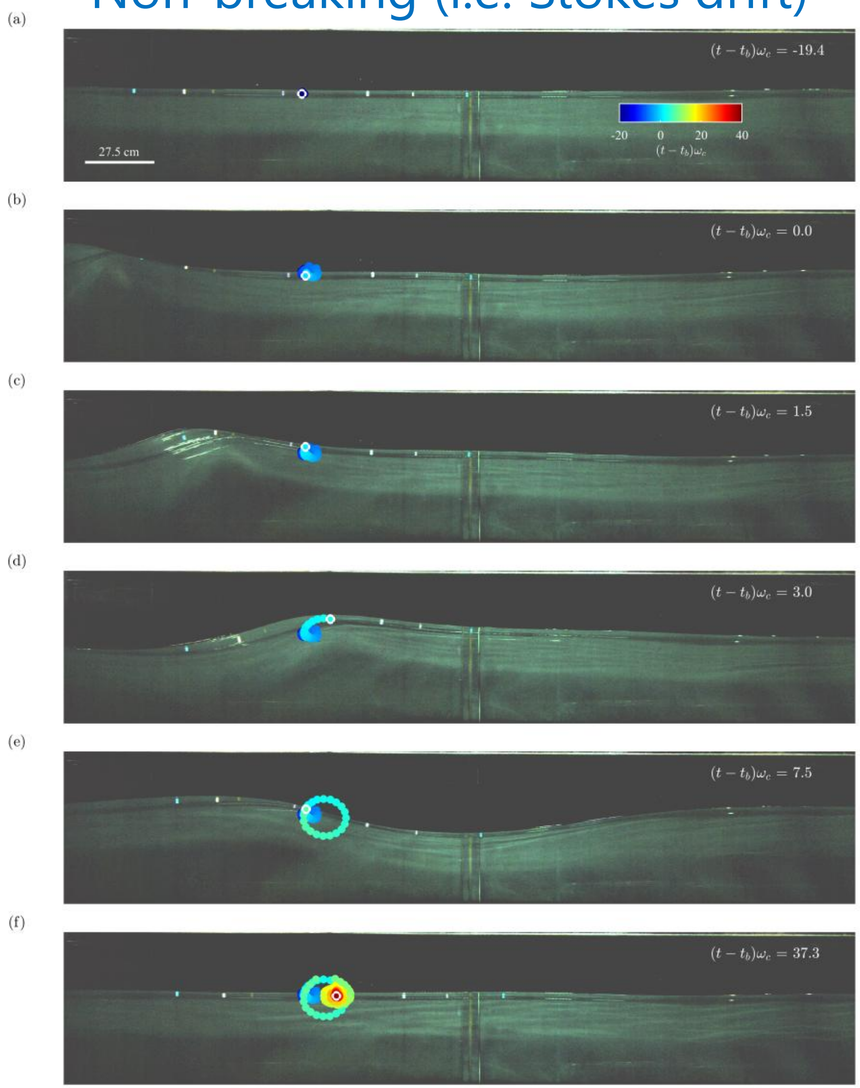
- Collecting in-situ measurements in such a rapidly evolving environment (both in space and time) over the broad range of scales of air-sea interaction processes has proven to be particularly challenging from traditional oceanographic platforms, while satellite products remain for now limited to coarse resolutions (temporal in particular).

- Unique observations (both lab and in-situ/airborne) provide better understanding wave–current interactions and wave breaking, including at submesoscale fronts.

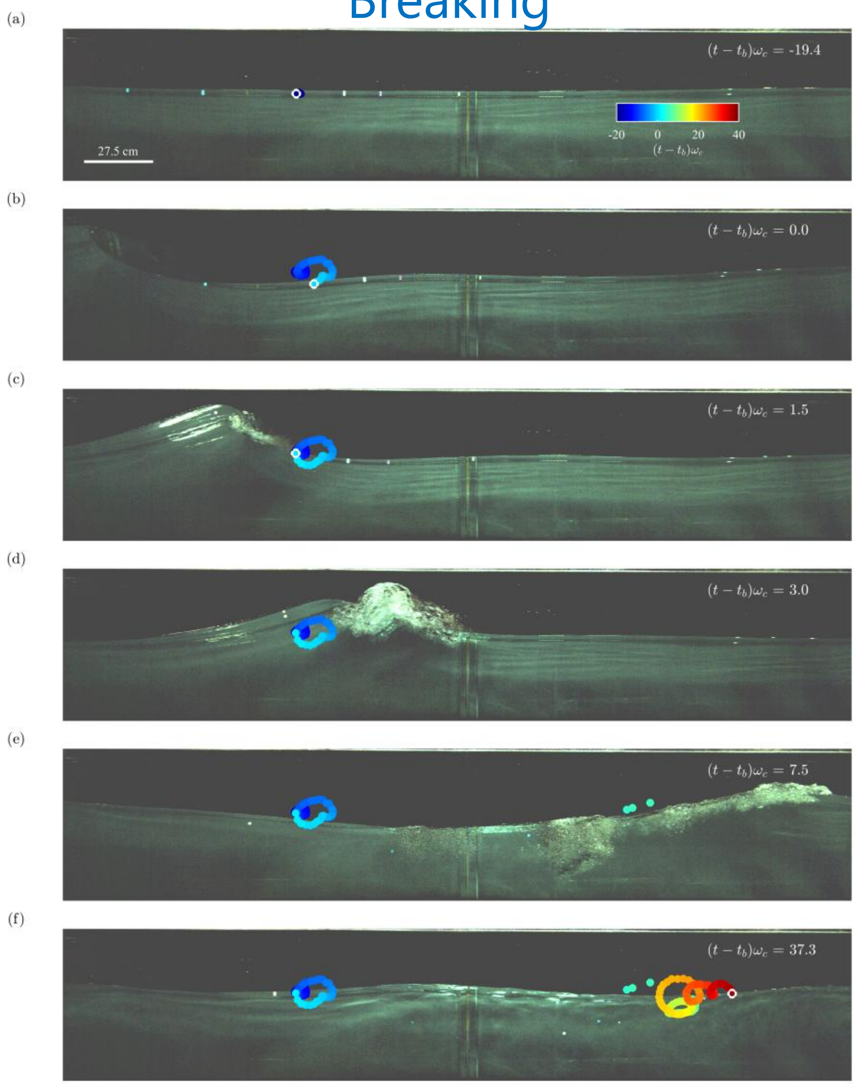
- We presented a novel instrument, DoppVis, capable of measuring surface currents down to 250m (and less!) horizontal resolution along with the standard remote sensing observations collected from the MASS.

Laboratory studies: Particle trajectories in focusing region of deep-water wave packet

Non-breaking (i.e. Stokes drift)

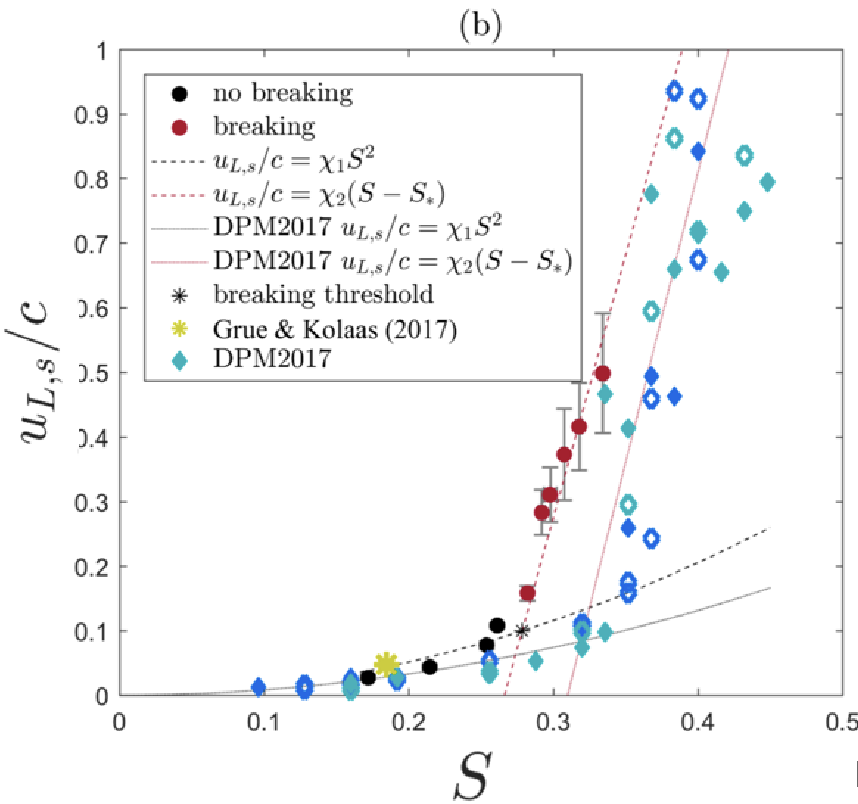


Breaking



Lenain et al. (2019, JFM)

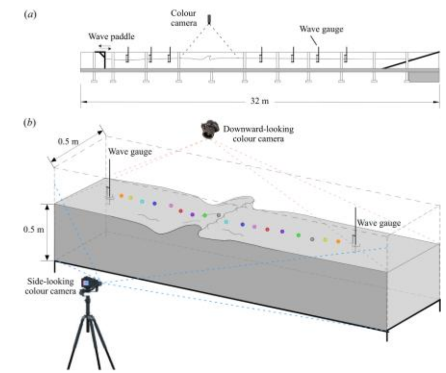
Particle trajectories in focusing region of deep-water wave packet



Lagrangian drift due to breaking may be nearly an order of magnitude larger than non-breaking waves

$\alpha_{\text{Lab}} = 8$

$\alpha_{\text{DNS}} = 9.5$



Based on model of Deike et al. (2017, DPM2017, JFM)

Drift induced by breaking, U_{LB}, reaches 30% of Stokes drift

What are the dynamical consequences of this additional transport on the submesoscale?

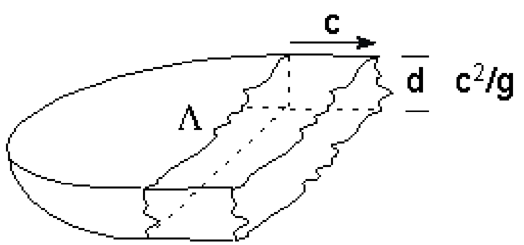
Lenain et al. (2019, JFM), Pizzo et al. (2019, JPO), Sinnis et al. (2021, JFM), Blaser et al. (in preparation)

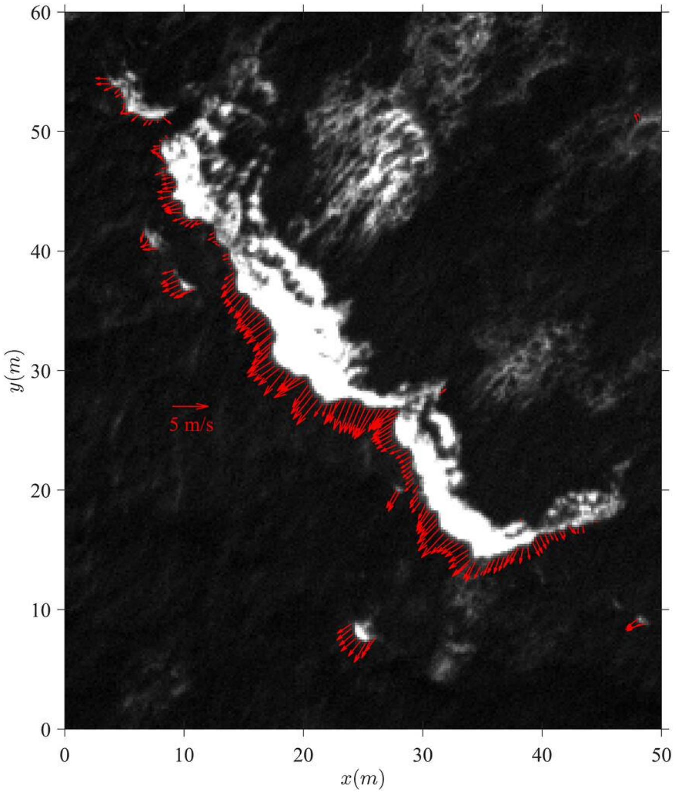
Phillips (1985) introduced the length of breaking fronts, $\Lambda(c)$, and its moments to characterize breaking statistics.

The first moment R represents the fraction of ocean surface turned over by breaking fronts per unit time.

$$R = \int \Lambda(c) \mathrm{dc}$$

R represents the fraction of ocean surface turned over by breaking fronts per unit time = Actively breaking whitecap coverage





Modulation of Surface Gravity Waves at a Submesoscale Front

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Phillips (1985) introduced the length of breaking fronts, $\Lambda(c)$, and its moments to characterize breaking statistics.

The first moment R represents the fraction of ocean surface turned over by breaking fronts per unit time.

$$R = \int \Lambda(c)\mathrm{d}c$$

Total length of breaking fronts per unit surface area: $L = \int \Lambda(\mathbf{c})\mathrm{d}\mathbf{c}$

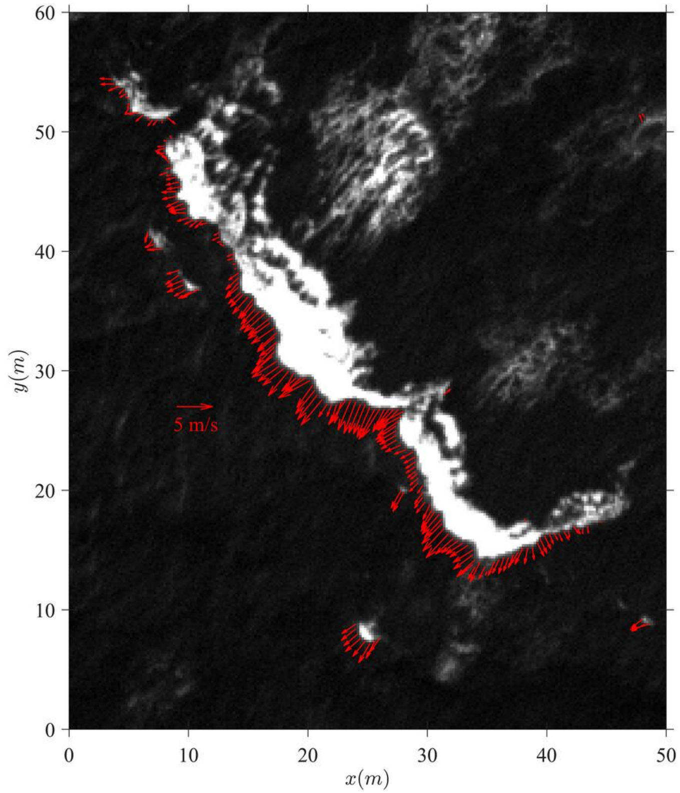
Fraction of total surface area turned over per unit time: $R = \int c\,\Lambda(\mathbf{c})\mathrm{d}\mathbf{c}$

Fractional whitecap coverage: $W \propto \int c^2\,\Lambda(\mathbf{c})\mathrm{d}\mathbf{c}$

Rate of air entrainment per unit surface area: $V_a \propto \int c^3\,\Lambda(\mathbf{c})\mathrm{d}\mathbf{c}$

Momentum flux per unit surface area: $M \propto \int c^4\,\Lambda(\mathbf{c})\mathrm{d}\mathbf{c}$

Energy dissipation per unit surface area: $E \propto \int c^5\,\Lambda(\mathbf{c})\mathrm{d}\mathbf{c}$,



Kleiss et al. (2009), Romero (2019), Vrecica, et al. (2022), Akaawase et al. (2025), Matsuyoshi et al. (in preparation)